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Ecosystem Services in urban areas: evaluating the role of green spaces to improve air quality using ecological indicators

Mestrado em Ecologia e Gestão Ambiental

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## Abstract

Air pollution has substantial impacts in human health. The air quality policies implemented in Europe during the last decades led to an overall decrease in pollution originated from industry. However, in general in urban areas traffic intensity is still significant, exposing urban citizens to various air pollutants. In face of the expected increase in the number of people living in cities, from current 54% to 66% in 2050, management actions to improve air quality in urban areas are imperative.

Urban green spaces are known to provide several ecosystem services, namely those associated to air purification. However, the quantification of this ecosystem service is still undone. Quantifying the role of green spaces in air purification requires information with high spatial and temporal resolution. Air quality monitoring stations in cities are scarce, due to their elevated costs, and the existent ones are far from providing an adequate spatial cover. The lack of air quality data with high spatial resolution and with consistent time-series matching the diversity of green space typologies, have been the main setback for this ecosystem service evaluation.

Ecological indicators are good candidates for monitoring ecosystem services in urban areas. Lichens are within the most widely used ecological indicators to monitor air quality, including in urban areas, due to their direct dependence of atmospheric conditions. They can be sampled in a flexible way in urban areas, providing high spatial resolution data and integrating the time component.

The aim of this study was to evaluate and model how green spaces can improve air quality in urban areas, using lichen as ecological indicators. The work was performed in Lisbon, a large city with multiple typologies of green spaces, and areas with variable atmospheric pollution levels. Lichen diversity was sampled following the standard European method in 42 green spaces stratified by size and location. Other environmental variables associated with green spaces and its surroundings were evaluated, such as vegetation density and surrounding urban density.

Lichen species richness in green spaces was very significantly related with most variables associated to air quality. Thus, this simple and very robust

metric was selected as ecological indicator of the effects of air quality in cities. Background pollution, likely from traffic, contributed to decreasing air quality. Conversely, high vegetation density in and around green spaces and large green spaces contributed positively to air quality in Lisbon green spaces. A model for air quality on Lisbon green spaces allowed us to determine that increasing their area or building small gardens greatly contributes for improving local air quality. Low air quality is an additional health risk for Lisbon population, particularly for the most vulnerable groups, such as elderly people (>65 years) and children (>14 years). Using the same model, we provided a health risk map for the most susceptible age groups of the population: elderly and children. Ultimately, this framework can be used as a tool for informed decisions in urban green spaces management aiming at air purification using ecosystem services.

**Keywords:** Lisbon, air pollution, gardens, lichens, green urban management

## Resumo

O número de pessoas a viver em cidades tem vindo a aumentar, tornando cada vez mais importante a questão da poluição associada às áreas urbanas. Os espaços verdes citadinos constituem zonas de lazer e de redução do *stress*, estando associados a diversos serviços do ecossistema, nomeadamente, a diminuição da poluição do ar. A densidade de árvores e o tamanho do espaço verde são geralmente considerados como muito importantes para esta capacidade. No entanto, há ainda um número reduzido de estudos que abordem os espaços verdes urbanos, principalmente os de pequena dimensão.

Este trabalho teve como objetivo analisar a importância dos espaços verdes na diminuição da poluição do ar em zonas urbanas. Com esse intuito construíram-se modelos de qualidade do ar para os espaços verdes utilizando indicadores ecológicos. Este trabalho foi desenvolvido em Lisboa, a maior cidade de Portugal, situada no centro do país. Este revelou-se um bom local de estudo devido à alta concentração de poluentes urbanos, ao elevado número de habitantes e à existência de uma grande diversidade de áreas verdes, principalmente nas áreas menos centrais. A quantificação da qualidade do ar nos espaços verdes desta cidade poderá contribuir para uma gestão mais eficaz e ponderada destes.

A amostragem de espaços verdes foi feita de forma aleatória e estratificada à zona, à área e à densidade de tecido urbano envolvente, de forma a não subamostrar zonas com menos espaços verdes, espaços verdes de dimensões elevadas ou com tecido urbano pouco denso. A amostragem de líquenes foi realizada em 42 espaços de verdes. Em cada espaço verde a diversidade de líquenes epífitos foi analisada nas 4 árvores mais próximas do centróide possível. Foi registada a frequência das espécies encontradas, seguindo um protocolo europeu *standard*. Quando a identificação no local não foi possível, foram recolhidas amostras para posterior identificação em laboratório. Foi ainda registado o diâmetro à volta do peito de cada árvore amostrada.

Foram tidas em conta várias métricas de biodiversidade: o valor de diversidade de líquenes (LDV), a riqueza, a riqueza funcional (FR). Foi calculada a área total de cada espaço verde e o NDVI (normalized difference vegetation index) do centróide de cada espaço verde e do conjunto do espaço

verde com um *buffer* de 100 metros em redor. As áreas foram obtidas através da análise de fotografias aéreas e os valores de NDVI através de imagens do satélite *Landsat 8*. Com o objetivo de ter em consideração a poluição de fundo do tráfego automóvel, foram utilizados dados das concentrações de dióxido de azoto (NO<sub>2</sub>) existentes nas diferentes zonas da cidade, calculadas num trabalho anterior.

As espécies de líquenes identificadas foram caracterizadas em diferentes grupos funcionais, de acordo com três atributos (*traits*): Tolerância à eutrofização, requisitos de humidade e forma de crescimento.

Por fim, foram recolhidos dados relativos à população da cidade, tendo em conta a faixa etária das respetivas freguesias. Os dados respeitantes à população com menos de 14 anos e com mais de 65 anos foram posteriormente tidos em conta para a produção de mapas de risco, tendo em conta a maior suscetibilidade à poluição destas faixas etárias.

O tratamento estatístico inicial dos dados envolveu a realização de coeficientes de correlação de spearman entre as variáveis ambientais e as métricas consideradas. Posteriormente foram elaborados modelos (GLM) tendo em conta apenas as variáveis com maiores associações. O modelo final foi selecionado tendo em conta o princípio da parcimónia e o maior valor de AIC. De seguida, o modelo, que tem como variáveis explicativas a área do espaço verde e a concentração de NO<sub>2</sub>, foi aplicado a 63 espaços verdes de Lisboa, para além dos realizados da amostragem inicial.

A métrica de biodiversidade Riqueza foi a que apresentou maiores associações com as variáveis ambientais. Assim, esta métrica, fácil de aplicar e muito robusta, foi utilizada como indicadora da qualidade do ar nos espaços verdes de Lisboa.

Os resultados obtidos sugerem que o NDVI do espaço verde e a área deste são fatores preponderantes para a qualidade do ar em espaços verdes urbanos. Também a poluição de fundo (provavelmente com origem automóvel) é de grande importância para a qualidade do ar nestes espaços. Estas foram as variáveis ambientais com maior correlação com as métricas consideradas.

No total dos espaços amostrados foram identificadas 22 espécies, valores semelhantes aos apresentados na bibliografia para outras cidades europeias. Em relação a um estudo anterior nos anos 70, a qualidade do ar em Lisboa

aparenta não ter sofrido grandes alterações, o que se poderá dever à diminuição dos poluentes emitidos por veículo, devido aos avanços tecnológicos, em simultâneo com o aumento do número de veículos em circulação desde os anos 70. No entanto, as diferenças no tipo de amostragem poderão ser relevantes e justificar estes valores. Relativamente aos grupos funcionais considerados, os líquenes xerófitos, oligotróficos e nitrófilos foram os obtidos em maior número, enquanto os fruticulosos foram os menos abundantes.

Foi ainda comparada a riqueza de líquenes, nos espaços verdes mais próximos das estações de qualidade do ar existentes em Lisboa, com as medições de  $PM_{10}$  no ano de 2013 em cada uma dessas estações. A riqueza de líquenes mostrou estar significativamente correlacionada com o número de períodos (20 dias consecutivos) de partículas acima dos  $10\mu g/m^2$ . Esta correlação linear permitiu-nos utilizar a riqueza de líquenes como um sorruagate da qualidade do ar dos espaços verdes.

Analisando o modelo obtido neste trabalho foi ainda possível estimar a melhoria do ar nos espaços verdes de Lisboa. Assim, inferiu-se que o mesmo aumento de área em espaços verde de dimensões pequenas é mais eficaz na redução da poluição do ar que em espaços verdes de grandes dimensões. Por exemplo, com 10% de aumento de área, num espaço verde de  $300m^2$  pode-se alcançar 14% de melhoria da qualidade do ar enquanto num espaço verde com  $50000m^2$  a melhoria ronda os 1,5%. Também foi possível verificar que em zonas com mais poluição de fundo a melhoria é mais potenciada do que em zonas com menos poluição de fundo.

Da análise da população das diferentes freguesias em Lisboa, concluiu-se que é na zona centro que existe as freguesias com maior percentagem de idosos e na periferia as freguesias com maior percentagem de crianças. De salientar, que a percentagem de idosos é bastante superior à de crianças e por isso estes devem ser tidos em conta mais atentamente. A zona central da cidade é também onde os espaços verdes possuem pior qualidade do ar, estimada pelo modelo criado neste trabalho. Assim, esta é uma zona que requer especial atenção por parte dos gestores dos espaços verdes. A criação de espaços verdes com maior tamanho e densidade de árvores ou a ampliação e readaptação de espaços verdes existentes são duas ações sugeridas. Em

situações de elevada densidade urbana, os telhados e as paredes verdes são boas possibilidades. Tendo em conta a influência do tráfego automóvel na poluição dos espaços verdes, é também sugerido medidas como, por exemplo, a diminuição de duas vias para uma só, substituindo a segunda por uma linha de árvores.

Palavras-chave: Líquenes, qualidade do ar, áreas urbanas, espaços verdes

## **Abbreviation list**

DBH - Diameter at breast height

LDV - Lichen Diversity value

FR - Functional richness

NDVI - Normalized Difference Vegetation Index

PSR - Potential solar radiation

NO<sub>2</sub> - Nitrogen dioxide

GLM - Generalized Linear Model

AIC - Akaike's Information Criterion

Slop - Slope

Alt - Altitude

Dist - Distance from the coast line

PM<sub>10</sub> - Particulate matter up to 10 micrometers in size





# 1. Introduction

Currently, more than half of world's population lives in cities and by 2050 this number is expected to increase by 66 percent (United Nations [UN], 2014). The fast and unprecedented cities' growth brought severe challenges to society, including environmental degradation, loss of natural habitat, and increased human health risks associated with heat, noise and pollution (Zupancic et al., 2015).

Despite the progress made in Europe during the last decades to implement strict air policies, substantial problems of air quality remain (European Environmental Agency [EEA], 2014), particularly in urban areas. The levels of classical and very toxic air pollutants such as sulphur dioxide from industrial emissions have substantially decreased. However, as a consequence of traffic, urban citizens remain exposed to various air pollutants such as nitrogen oxides, volatile organic compounds, particulate matter and photochemical oxidants (Fenger, 2009). Air pollution costs both money and health to city's inhabitants. Estimations show that in 2012 more than 400 000 premature deaths were attributable to air pollution in Europe (World Health Organization [WHO], 2014). In Portugal alone, the economic costs of deaths from air pollution in 2010 were estimated to be around 8,5 million euros, half of which associated to air pollution derived from road transport (WHO, 2014). In the same year, 38 003 deaths in Portugal were attributed to air pollution (Organisation for Economic Co-operation and Development [OECD], 2014). It is clear that air pollution in cities represents a serious environmental problem and its mitigation a major public challenge. Therefore, improving air quality has substantial, quantifiable and important civic health benefits (Chen & Kan, 2008).

Within human population, some age groups show a higher vulnerability to air pollution. Higher health risks were demonstrated in the elderly (> 65 years), when comparing to the rest of the population. For instance, increased pollution exposure in the elderly was associated with increased mortality by cardiopulmonary or respiratory causes and with an increased number of

hospital admissions and emergency-room visits (Simoni et al., 2015). Children (< 14 years old) may also have a greater potential for adverse health effects, when compared to adult population. Children's ongoing development makes them more susceptible, and differences in their metabolism and behavior may cause them to reach higher levels of exposure when exposed in the same environment as adults (Selevan et al., 2000).

Ecosystem based solutions can be used to improve air quality in a cost-effective way, and can work synergistically with more demanding air policies. Ecosystem services can be defined as the benefits human populations derive from ecosystem functions, directly or indirectly (Costanza et al., 1997). Green spaces provide numerous ecosystem services in urban areas: air filtration, microclimate regulation, noise reduction, rainwater drainage, recreational and cultural values, among others (Bolund & Hunhammar, 1999; Jansson et al., 2014). For example, a study in the UK showed that a 10 percent increase in tree cover in mid-size cities could increase about 12 percent of the existing vegetation carbon stock (Davies et al, 2011). Urban green spaces also play an important role in the lives of people inhabiting cities, such as reducing stress (Ulrich et al., 1991) and restoring the capacity of citizens to focus (Berto, 2005), among others. Morancho (2003) showed an inverse relationship between the selling price of a residence and its distance from an urban green space. This hedonic valuation suggests that people have a preference for living next to green spaces. Decision-makers and politicians are progressively aware of the importance of urban ecosystem services for human health and well-being in cities. However, the way to measure the benefit of those services with high spatial resolution for decision-making remains an open question (Lakes & Hyun-Ok, 2012). This is especially relevant for air quality, which can change radically over very short distances. Thus, an open question remains, how much can a green space produce the service of air purification?

It is already known that green spaces can purify air both by direct and indirect mechanisms. Directly, through the filtering effect of plants, mainly based on dry deposition of pollutants through stomata uptake or non-stomatal deposition on plant surfaces (Gheorghe & Ion, 2011). Indirectly, mainly by improving urban ventilation, which in turn amplifies the dispersal of the

pollutants (Givoni, 1991). Although vegetation can purify the air, the extent of that reduction depends on local conditions (Svensson & Eliasson, 1997). For instance, it was shown that higher densities of tree canopies in forest parks decrease PM<sub>10</sub> concentration inside them (Cavanagh et al., 2009). However, this study was based on a single urban green space. Bowler et al. (2010) identified gaps in the literature that include shortage of data on the optimal size, allocation and characteristics of the green spaces that can contribute to improve urban areas for human health, namely in reducing human exposure to ground level ozone concentrations. A recent systematic review found only a few studies on the mitigation of pollution impacts by small urban parks (Zupancic et al., 2015). But importantly, among all works reviewed, all types of green spaces were positively related with air purification, from small green walls to large-scale urban forests.

To study how green spaces purify the air, long-term measures of atmospheric pollutants should be used. However, only a few air quality stations are available due to its high operating costs. As a consequence, the available air quality data has insufficient spatial resolution, and those stations are rarely associated to green spaces. As an example, in the city of Lisbon only 6 stations are operating, and measuring a limited number of pollutants. The most recent station is available only since 2000 and not all stations measure the same pollutants. The low number of stations translated in a lack of high spatial and temporal resolution, make it extremely difficult to understand the role of green spaces in purifying air in cities.

A solution to overcome this problem is the use of ecological indicators. They allow measuring the effect of green spaces on air pollution reduction, by retrieving information with high spatial resolution and in a flexible way. Ecological indicators can be used to assess the condition of the environment or to monitor trends in condition over time, to provide an early warning signal of changes in the environment, or to diagnose the cause of an environmental problem (Dale & Beyeler, 2001). An ecological indicator can be included under the concept of surrogate, which is a component of the system of concern that can be more easily assessed or managed than others, and that is used as an indicator of, for instance, the quality of that system (Mellin et al., 2011; Caro et al., 2010; Lindenmayer et al., 2015).

Lichens are a symbiotic association between a fungus and an algae and/or cyanobacteria (Honegger, 1991). Lichens lack roots, taking up water, solutes and gases over the entire thallus surface, and so depending on the atmosphere for nutrition (Hauck, 2010). Moreover, their lack of cuticle and stomata means that the different contaminants are absorbed over the entire surface of the organism (Hale, 1983). Consequently, lichens have been extensively used for monitoring air quality as they respond to atmospheric pollutants directly, being defined as “permanent control systems” for air pollution assessments (Nimis et al., 1989; 2002). Lichens were used as ecological indicators in physiological studies, as bioaccumulators of pollutants, and in biodiversity studies, since species show different sensibilities to air pollutants (Branquinho, 2001). For instance, in the Portuguese city Almada, lichens showed to be related to the city’s microclimatic gradient, and its functional diversity regarding water requirements responded in an integrated way to the climatic modifications occurring in the city, namely the heat island effect (UHI) and the alleviation effect of forested areas (Munzi et al., 2014).

Several biodiversity metrics using lichens can be applied when analyzing air quality, such as total diversity or functional diversity, by means of functional traits and functional groups (Nimis et al., 2002). Both measures of total diversity and functional diversity were already used to evaluate the effects of environmental change in ecosystems (Giordani, Brunialti & Alleteo, 2002; Pinho et al., 2011; Pinho et al., 2012; Pinho et al., 2014). Total diversity metrics include species richness (the number of species) and the lichen diversity value, LDV (a measure of species frequency) (Asta et al., 2002); while functional diversity metrics (the diversity of species traits in ecosystems), can include measures of functional richness (Schleuter, 2010) or the LDV of each functional group (Pinho, 2009). Functional richness can be measured as the number of functional groups (Villéger & Mouillot, 2008). Functional traits are the characteristics of an organism that are considered significant to its response to the environment and/ or its effects on ecosystem functioning (Diaz & Cabido, 2001). Functional groups are composed by a set of species with either similar responses to the environment or similar effects on major ecosystem processes (Gitay & Noble, 1997). An example could be

the lichen response trait “tolerance to drought” and its division into hygrophyte and xerophyte functional groups (Llop et al., 2012). Nevertheless, the most reliable metrics to be used in urban areas and the way atmospheric pollution affects them remains largely unstudied (Davis et al., 2007).

The aim of this work was to evaluate and model with high spatial resolution the role of green spaces in improving urban air quality. We used lichens as ecological indicators of atmospheric pollution, using several metrics of biodiversity measured in green spaces with different characteristics (size, surrounding urban density, vegetation density). Finally, we intended also to make a health risk assessment, at the parish size, for the most susceptible age groups of the population, the elderly and children. Increasing the capacity to minimize air pollution using green spaces would be a great contribution to citizens. Therefore, this work also aims to propose management practices oriented to increase green spaces capacity to purify air.

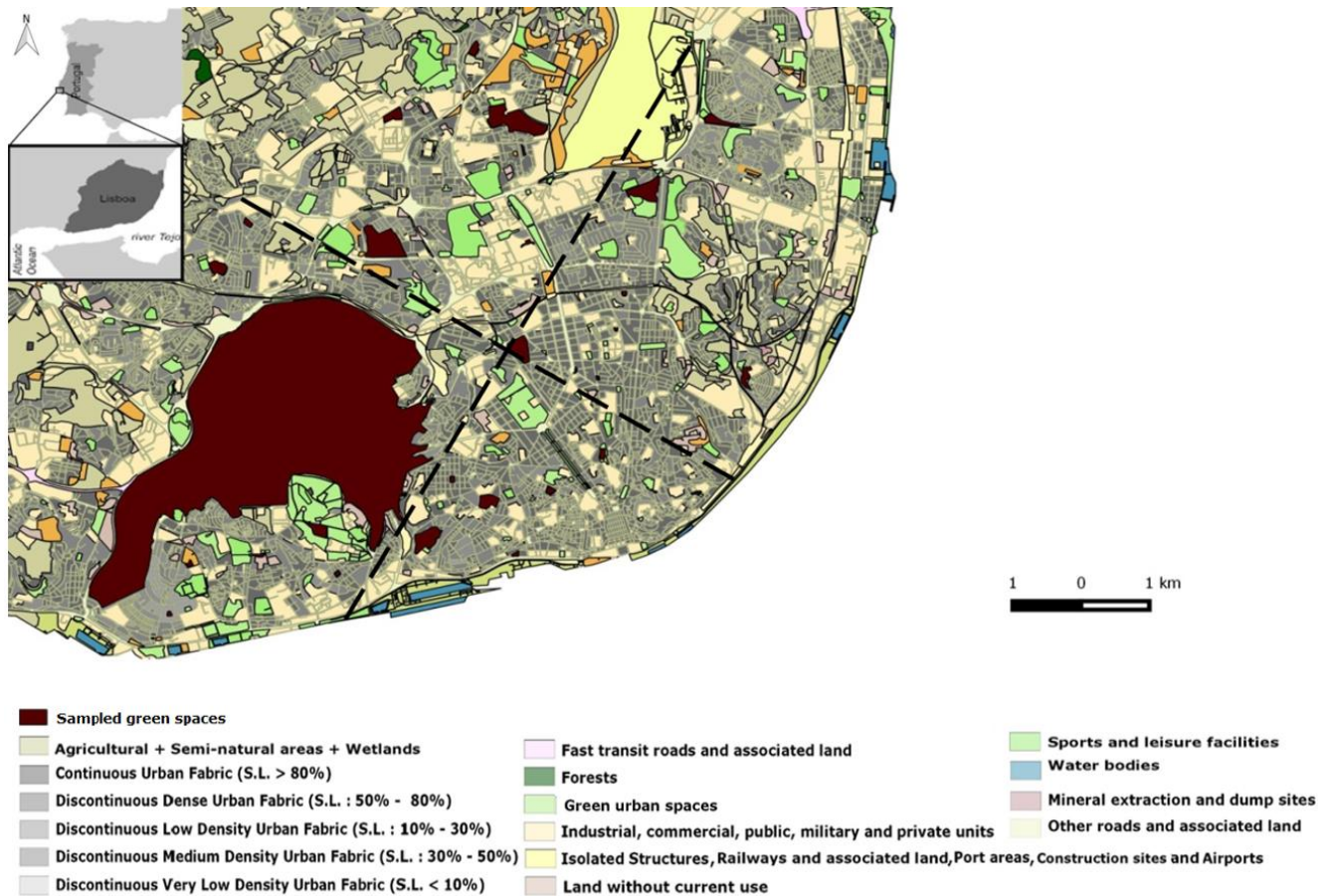
## **2. Methods**

### **2.1 Study area**

This work was done in Lisbon, a city located on the western coast of Portugal, on the right bank of the Tagus River. Lisbon has a population of 2821876 residents in its metropolitan area (Instituto Nacional de Estatística [INE], 2011). This city is characterized by a Mediterranean climate, with an annual mean temperature of 17,1°C and mean annual precipitation of 788,3 mm (1960-2014 average; Base de Dados de Portugal Contemporâneo [PORDATA], 2015), with north and north-western prevailing winds.

### **2.2 Sampling design**

Prior to the selection of sampling sites, a complete cartography of Lisbon's green spaces was done. As the European Urban Atlas contemplates only large green spaces (>1 ha), smaller green spaces were added to the cartography by manual photo interpretation of aerial photographs. From all existing green spaces, a sub-sample was selected in a randomly stratified way. Sites were stratified by location, urban density and green space area. This was done to prevent oversampling the most frequent green spaces, i.e. those located in city periphery, surrounded by low density urban areas and with small size. For stratification by location, the city was divided into four quadrants (Figure 1), each with a similar number of green spaces. In each of these four quadrants, green spaces were distributed into five classes considering the histogram of all green spaces area. The following classes were considered: 0-0.1, 0.1-0.5, 0.5-10, 10-40, and higher than 40 ha. Stratification by urban density considered 100 meters buffers around each green space and high resolution land cover information for each buffer was retrieved from the European Urban Atlas. The following land cover categories were considered to classify the area surrounding green spaces as high density: continuous urban fabric; industrial, commercial, public, military and private units; discontinuous dense urban fabric. The remaining land cover categories in the area surrounding green spaces were considered as low density. Finally, for each class of area within each quadrant, two green spaces were randomly chosen, one with surrounding high urban density and another with surrounding low urban density (N=40). After this selection another two green spaces were added: Parque florestal de Monsanto (by far the largest green space in the city, two orders of magnitude larger than the others) and Avenida da Liberdade (considered the most polluted area in Lisbon). As a result, a total of 42 sampling sites were selected.



**Figure 1:** Study area showing the distribution of the sampled green spaces (N=42) and city's land cover. Dashed lines divide the study area in the four quadrants considered for the stratification by location.

## 2.3 Data collection

### 2.3.1 Lichen sampling

Epiphytic lichen diversity was surveyed in the four suitable trees closest to the centroid of each green space. The centroid of each green space is the most comparable point between all green spaces, as it is always the most protected place (Hamber et al., 2008) and, therefore, the one with higher potential for air pollution reduction.

The enormous diversity of tree species in Lisbon green spaces prevented the use of a single phorophyte, as suggested in by the sampling method (Asta et

al., 2002). To minimize the potential confounding factors caused by this, only phorophytes with medium bark roughness were selected.

Tree selection followed standard conditions: trunk inclination with a deviation from vertical inferior to ten degrees; circumference at breast height higher than 50 cm; with a clear area on the trunk at this height, without damage, decortication, branching, knots, or other epiphytes preventing lichen growth. A grid with five squares, each with 10 x 10 cm, was attached to the trunk of each tree at the four main cardinal points, of the lowermost part at 1 m above ground, adapting the sampling procedure of the standard European protocol (Asta et al., 2002). Each lichen species occurring inside each grid cell was identified and recorded, or collected for later laboratory identification. Lichen species frequency was recorded as the number of grid cells (out of 20 possible) where each species was detected.

Lichen species richness was calculated as the total number of species in each green space. Lichen Diversity Value (LDV) was calculated for each tree as the sum of all species frequencies. The species frequency and the LDV of each green space (LDVt) represent the average of the four sampled trees.

Species nomenclature follows Nimis & Martellos (2008). Tree diameter at breast height and the GPS coordinates of each tree were recorded.

### **2.3.2 Environmental variables**

The Normalized Difference Vegetation Index (NDVI) is used to estimate vegetation density and condition, being one of the most widely used vegetation-related metrics (Bernan et al, 2011). NDVI values range from -1 to +1, with negative values corresponding to an absence of vegetation (Myneni et al., 1995). To estimate the density of the vegetation in each green space and in the surrounding 100 meters, satellite images taken from Landsat 8 (30 meters resolution) in May 2015 were analysed using the reflectance of bands 5 and 4, corresponding to the near infrared and visible. The reflectance of the two bands was calculated according to the following formula, where  $P_{\lambda}$  = Top of atmosphere planetary reflectance,  $\theta_e$  = Local sun elevation angle,  $M\rho$  = Band-specific multiplicative rescaling factor from Landsat metadata,  $A\rho$



= Band-specific additive rescaling factor from Landsat metadata and  $Q_{cal}$  = Quantized and calibrated standard product pixel values.

$$\rho_{\lambda} = \frac{M\rho \times Q_{cal} + A\rho}{\sin(\theta_e)}$$

NDVI was calculated using bands reflectance, using the following index.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

Afterwards, the average NDVI of the green space, and in the surrounding 100 meters buffer, was determined and used in subsequent analysis.

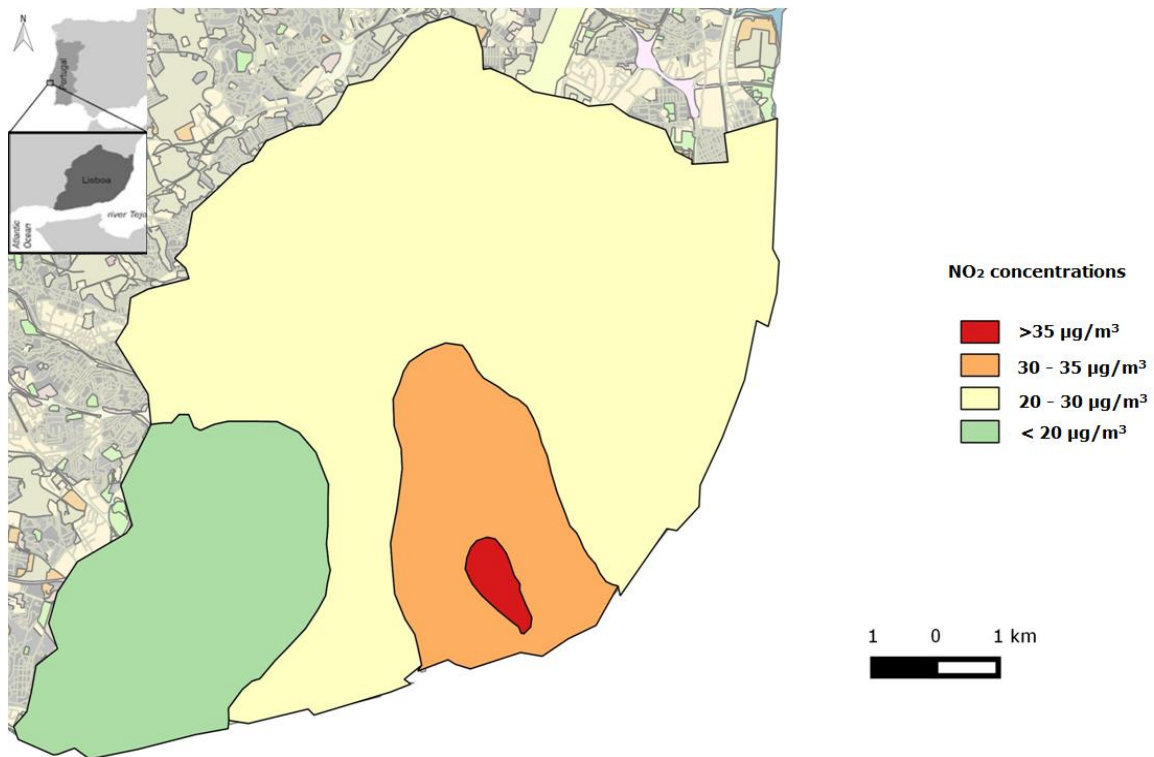
Each green space was analysed by manual photo interpretation of aerial photographs to calculate the percentage of area in each green space that was covered by buildings, pavements or areas with no vegetation (NVeg).

Urban density around each green space was also calculated for both 50 and 200 meters buffers, using the land cover categories considered to classify the area surrounding green spaces in the 100 meter buffers (see 2.2 Sampling design; U50, U100 and U200).

The average altitude (m), slope ( $^{\circ}$ ) and potential solar radiation (Wh/m<sup>2</sup>, used here as a surrogate of local microclimate) were calculated from a digital elevation model, derived from hypsometric curves with 10 meters interval. The Euclidian distance to the river was obtained using the information provided in the national database Atlas da Água.

A map of NO<sub>2</sub> concentration in the city of Lisbon (Mesquita, 2009) was used to estimate air pollution at each green space. The map was interpolated by ordinary kriging of measured NO<sub>2</sub> concentrations in 2002 and 2003. Concentration values were retrieved from air quality stations and diffusion tubes distributed across the city. Based on this information, we built a map with four classes of NO<sub>2</sub> concentration and the concentrations for each green space was determined (Fig. 2). For all analysis we report the classes using the values from 1 (to the lower concentration class) to four (to the high concentration class).

NO<sub>2</sub>, U50, U100 and U200 were considered as surrogates of anthropogenic pressure (human activities which can generate air pollution), namely car traffic and intensity of urban matrix use surrounding the green space.



**Figure 2.** Map of Lisbon's NO<sub>2</sub> concentration overlaid on the city's land cover. Four classes of NO<sub>2</sub> concentration were considered : < 20 µg/m<sup>3</sup> – class 1; 20 - 30 µg/m<sup>3</sup> – class 2; 30 - 35 µg/m<sup>3</sup> – class 3; >35 µg/m<sup>3</sup> – class 4 (adapted from Mesquita, 2009).

### 2.3.3 Demographic population data

Information on Lisbon population was collected by residence area and age. Data was retrieved from last Census in the city (INE, 2011). It is important to refer that when the Census information was compiled, city's administrative boundaries at the parish level were different from the current ones. To preserve consistency, old Census boundaries at the parish level were considered in all maps.

#### **2.3.4 PM<sub>10</sub> data**

Data on atmospheric particulate matter inferior to 10 micrometers size (PM<sub>10</sub>) was obtained from the environmental Portuguese agency online data base QualAr (<http://qualar.apambiente.pt/>). The records include hourly concentrations in five of the six stations located in Lisbon for 2013. Data were treated in the following way. For each twenty sequential PM<sub>10</sub> measures, the number of measurements with 10 µg/m<sup>3</sup> or more was recorded. At end of the year we considered the number of 20 sequential measurements that were all equal or above 10 µg/m<sup>3</sup>.

#### **2.4 Lichen functional diversity**

Lichen species were classified according to three response traits: humidity requirements, type of growth form and eutrophication tolerance. Functional group classification was based on the Italian database (Table 1; Nimis & Martellos 2008).

Species functional group classification was combined with species frequency data to obtain the LDV for each functional group at each green space. In addition, functional richness (FR) was also calculated for the set of traits growth form, humidity requirements and eutrophication tolerance. As these traits are categorical, FR corresponds to the number of functional groups present at each site.

**Table 1.** Traits and related functional groups following Nimis & Martellos 2008. Species maximum tolerance was considered for the humidity requirements and eutrophication tolerance.

Trait	Functional group	Description
<b>Humidity requirements</b>	Hygrophytic	From high to rather high humidity requirements
	Mesohygrophytic	Medium humidity requirements
	Xerophytic	From low to rather low humidity requirements
<b>Growth form</b>	Crustose	Firmly and entirely attached to the substrate by the lower surface
	Leprose	Like crustose but surface thallus with a granular mass appearance and always decorticated
	Squamulose	
	Foliose narrow-lobed	
	Foliose broad-lobed	Composed of small scales
	Fruticose	Partly attached to the substrate with a leaf-like form and narrow lobes
<b>Eutrophication tolerance</b>	Nitrophytic	Same as foliose narrow-lobed but with broad lobes
	Mesotrophic	3D-like structure, attached by one point to the substrate and with the rest of the thallus protruding from the surface of the substrate
	Oligotrophic	From tolerant to high eutrophication to very high eutrophication
		Weak eutrophication
		From sensitive to eutrophication to very weak eutrophication tolerance

## 2.5 Data analysis

Spearman  $\rho$  correlations between biodiversity metrics and environmental variables were calculated to account for possible nonlinearity in the relationships. Correlations were considered significant for  $P < 0.05$ . The

metrics and the environmental variables with higher correlations to biodiversity variables were selected for further analysis. This analysis allowed the selection of the most promising biodiversity metrics to be used as ecological indicators of the pollution effects. It is important to refer that green spaces area values were logarithmized prior to the analysis.

A General Linear Model (GLM) was used to predict air quality based on the environmental variables. The selected lichen variable(s) were modelled with the selected environmental predictors. The GLMs were popularized by McCullagh and Nelder, 1989. In this type of models the relationship between the response variable Y and the values of the X variables is assumed to be:

$$Y = b_0 + b_1X_1 + b_2X_2 + \dots + b_kX_k$$

In GLM the dependent variable does not need to be normally distributed and normally distributed error terms are not assumed. Moreover, in STATISTICA the GLM outline allows a simpler treatment of all possible predictor variables combinations and a quick comparison of the various models. GLM models are fitted via Maximum Likelihood estimation.

As pointed out by Burnham & Anderson (2001), three principles regulate our ability to make inferences in science: simplicity and parsimony; several working hypotheses; strength of evidence. The principle of parsimony was used in the selection of the models. From the models built with the significant variables, the selected model was chosen ensuring a small number of variables with the highest Akaike Information Criterion (AIC) value. An effect of interaction (first used by Fisher, 1926) occurs when a relationship between two or more variables is modified by at least one other variable. Interactions significance between the environmental variables was tested to assess if those relationships were important in model construction.

The model cross-validation was performed by randomly partitioning the original sample into 10 subsamples, with approximately 10% subsets of the original values. The new model calculations were performed with the remaining 90% observed values. Ten new equations were generated for the model, which were then used to predict the values at the excluded points.

The results from the 10 subsamples were averaged to produce a single estimation. Afterwards, the average difference between the predicted and the observed values was compared.

In order to analyze the association between the lichens richness and the green spaces air quality, the number of periods (20 consecutive days) with  $PM_{10}$  above  $10\mu g/m^3$ , measured in the air quality stations over 2013, were plotted with the number of lichen species observed in the small green spaces ( $< 1$  ha) closest to each air quality station.

The model was then used to test the effect of increasing 10% in the area of the green spaces on lichen species richness. This was done using the model previously developed (see Mesquita, 2009) fixing for 3 classes of  $NO_2$  ( $< 20 \mu g/m^3$ ,  $20 - 30 \mu g/m^3$  and  $30 - 35 \mu g/m^3$ ) present in Lisbon.

The selected model was applied to 63 unsampled green spaces across the city to predict air quality in those spaces and also to the 42 previously sampled, resulting in more than 100 green spaces considered. Finally, health risk maps were built joining demographic population data for each Lisbon parishes and the averaged estimated lichen species richness of the green spaces in the same subdivisions. Parishes with simultaneously low lichen species richness and high percentage of vulnerable population (elder people and children) were considered as high risk. Subdivisions with high lichen diversity (more than 8 species) were considered as low risk independently of the percentage of vulnerable population. The remaining subdivisions were considered as medium risk.

## **2.6 Software used**

Statistical analyses were performed with STATISTICA v12 (StatSoft, Inc.). Maps were built using QGIS geographic information software v2.4.0 (QGIS, Inc.). Functional richness (FR) was calculated using the 'dbFD' function of the CRAN software R (R Core Team 2013) FD package (Laliberte & Legendre 2010).

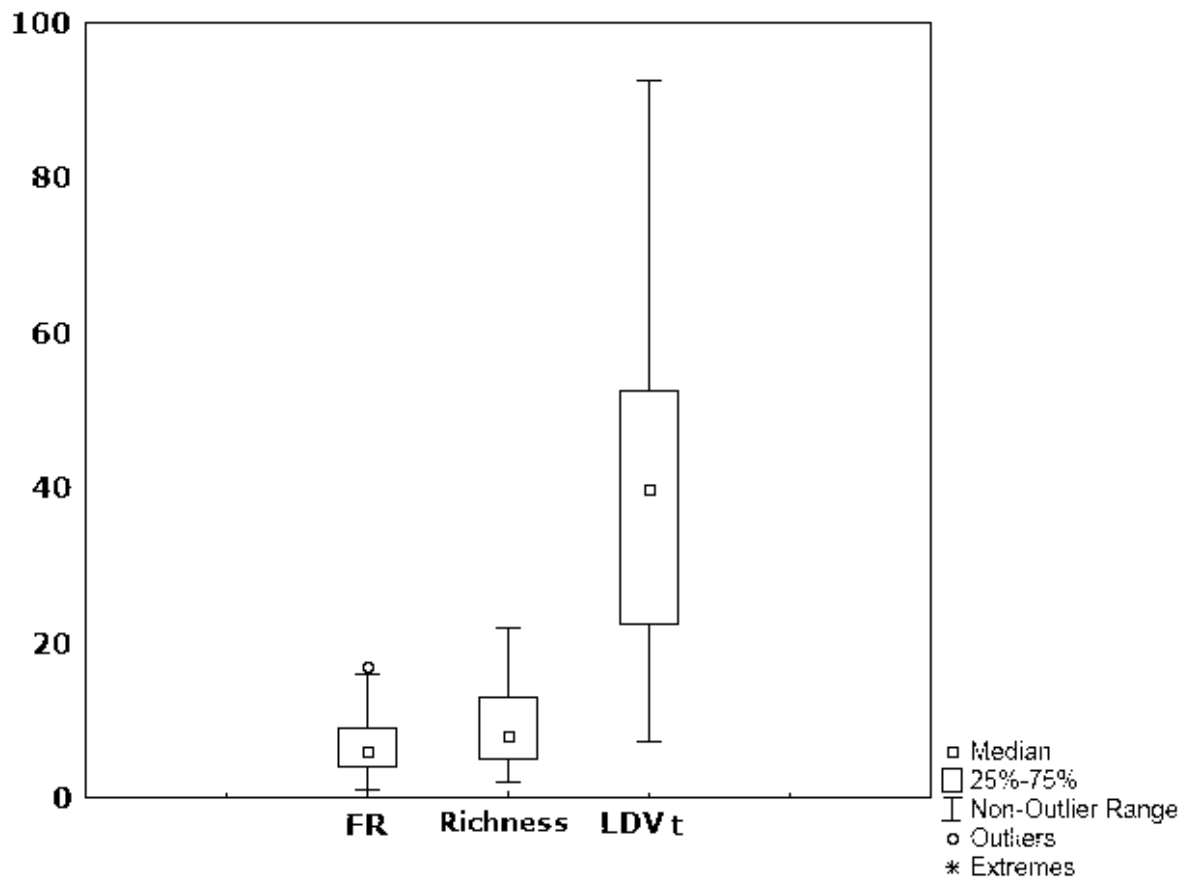
### 3. Results

#### 3.1 Green spaces and total lichen diversity metrics characterization

Lisbon green spaces areas ranged in three orders of magnitude from 287,21 m<sup>2</sup> to 228 365,10 m<sup>2</sup> (N=42; SD= 52 567,97; Table 2) without considering Monsanto, the largest of them all with an area of 1,12E7 m<sup>2</sup>.

**Table 2.** Descriptive statistics of environmental and biodiversity variables analyzed. Environmental variables: Alt (altitude), Arealog (green space logarithmized area), DBH (diameter at breast height), U50/100/200 (percentage of high urban density in 50/100/200 m buffer surrounding the green space), NO<sub>2</sub> (class of NO<sub>2</sub> atmospheric concentration), NDVIb (NDVI in a 100 m buffer surrounding the green space), NDVIc (NDVI in the centroid of the green space), Dist (distance from the coast line), Slop (slope), NVeg (percentage of area in the green space covered with no vegetation). Biodiversity variables: Richness (number of species), FR (functional richness). N=42.

	Mean	Minimum	Maximum	Std.Dev.	Coef.Var.
<b>Alt (m)</b>	65,88	0,26	119,34	33,21	50,41
<b>Arealog</b>	3,90	2,46	10,05	1,27	32,57
<b>DBH (cm)</b>	115,07	56,25	201,00	32,77	28,19
<b>Dist (m)</b>	4,28	0,59	201,00	33,25	28,90
<b>NO<sub>2</sub></b>	2,12	1,00	4,00	0,77	36,41
<b>NDVIb</b>	0,19	0,06	0,33	0,06	31,91
<b>NDVc</b>	0,31	0,05	0,45	0,10	32,63
<b>Slop (°)</b>	4,28	0,59	12,84	2,88	67,20
<b>PSR (Wh/m<sup>2</sup>)</b>	2039586	262987	2903120	621609	30,48
<b>U50 (%)</b>	50,65	0,00	90,05	24,93	49,22
<b>U100 (%)</b>	55,36	4,04	90,92	24,86	44,91
<b>U200 (%)</b>	37,45	8,15	91,75	19,81	52,90
<b>NVeg (%)</b>	17,29	0,00	101,00	22,23	18,22
<b>Richness</b>	9,19	2,00	21,00	5,25	57,15
<b>FR</b>	6,34	1,00	16,00	3,84	60,62
<b>LDVt</b>	38,81	7,25	83,75	19,189	49,44

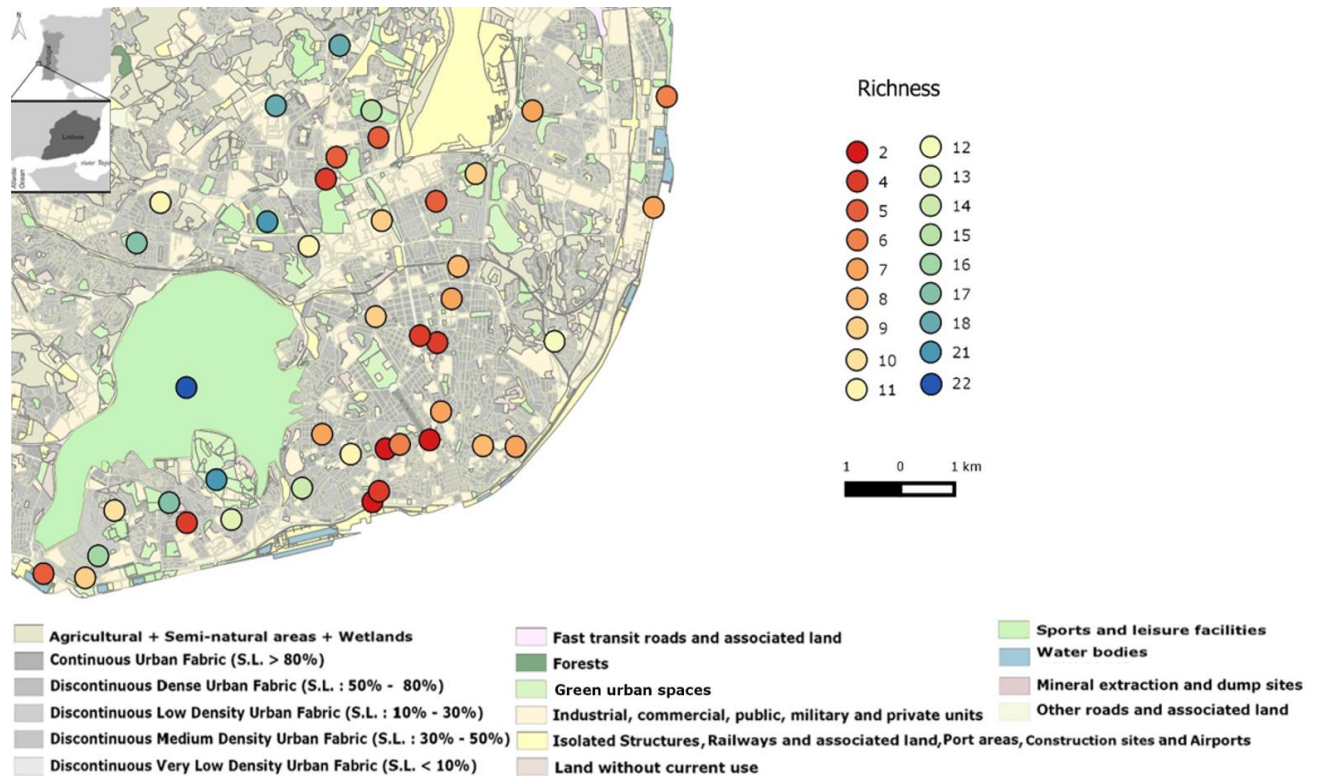


**Figure 3.** Boxplots of lichen diversity metrics evaluated in Lisbon green spaces: Richness (number of species), LDVt (total lichen diversity value) and FR (functional richness).

The number of lichen species sampled in Lisbon green spaces varied between 2 and 22 ( $N=42$ ;  $SD=5,34$ ) (Lichen species sampled shown in appendix I). Total lichen diversity value, LDVt, ranged from 7 to 92 ( $N=42$ ;  $SD=19,85$ ) and lichen functional richness ranged from 1 to 17 functional groups ( $N=42$ ;  $SD=4,14$ ) (Figure 3). These results show the considerable range of lichens species richness in Lisbon, from almost inexistent, to relatively rich sites. Descriptive statistics of lichen diversity metrics can be seen in figure 3.

The map in figure 4 illustrates the number of lichen species measured in each green space. Spatially, green spaces in downtown showed a lower number of lichen species, in contrast with those located in the west part of the city. These green spaces with higher richness were also those with larger areas.

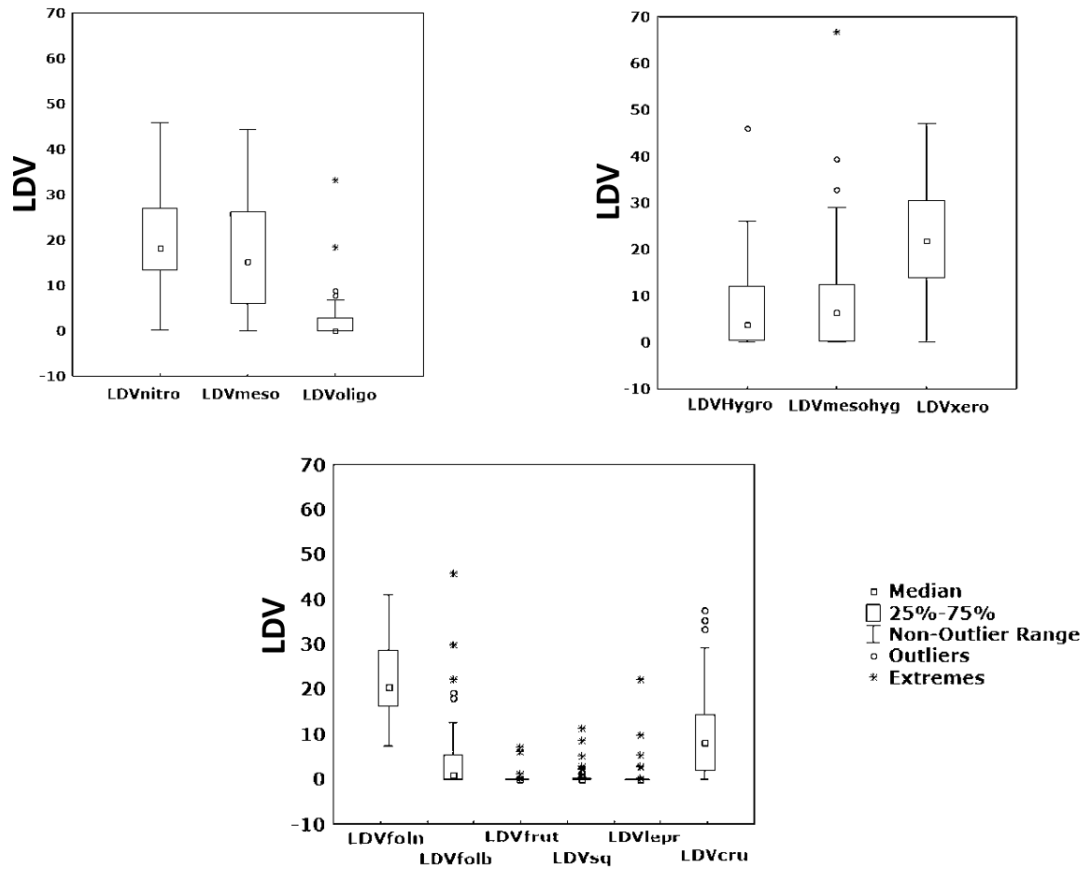




**Figure 4.** Land-use map of Lisbon with green spaces colored in green. Colored circles represent lichen species richness in sampling sites, ranging from the lowest in red, to the highest in blue.

### 3.2 Lichen functional diversity metrics

Lichen functional groups overall abundance in Lisbon green spaces were considerably different. Nitrogen (LDVnitro and LDVmeso) and xerophyte (LDVxero) lichen functional groups were more abundant in urban areas. Foliose and crustose lichen species were the most abundant growth forms in Lisbon green spaces (Figure 5).



**Figure 5.** Boxplots of the lichen diversity value (LDV) of each functional group considered: LDVHygro (hygrophytic); LDVmesohygro (mesohygrophytic); LDVxero (xerophytic); LDVnitro (nitrophytic); LDVmeso (mesotrophic); LDVoligo (oligotrophic); LDVcru (crustose); LDVfoln (foliose narrow); LDVfolb (foliose broad); LDVfrut (fruticose); LDVsq (squamulose), LDVlepr (leprose).

### 3.3 Explaining biodiversity patterns

Individual spearman correlations were calculated to determine which factors underlie lichen diversity patterns previously observed. Table 3 shows the most significant correlations between environmental variables and lichen biodiversity metrics.

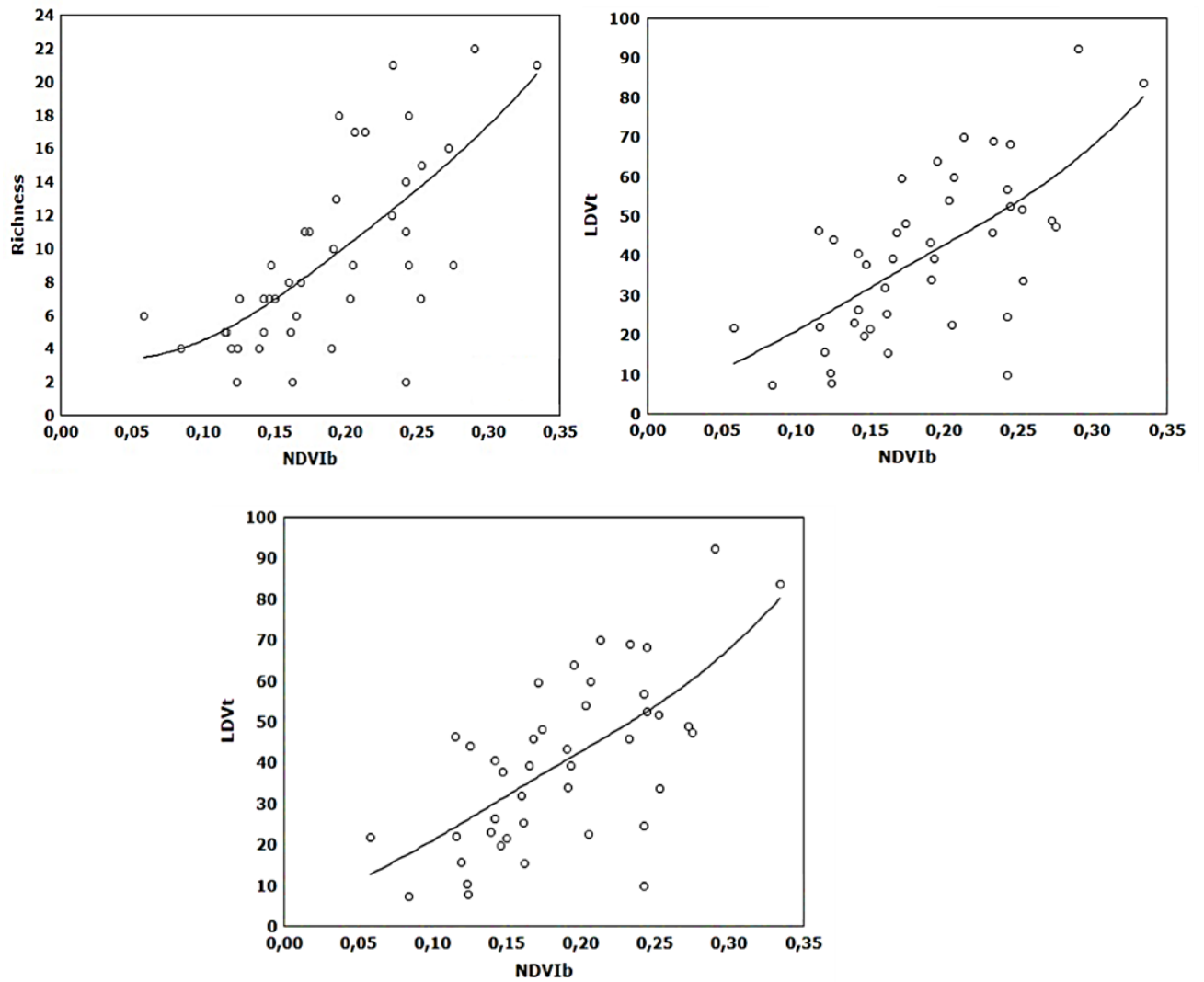
The best biodiversity metrics (i.e. the highest and most significant ones) were based in measures of total lichen diversity, such as lichen species richness and LDVt (Table 3). Within functional diversity, functional richness (FR) showed the highest correlation coefficient with the environmental variables. The tolerant lichen functional groups in terms of eutrophication or water

requirements, nitrophytic and xerophytic, did not significantly correlate with green spaces area, NDVIb or atmospheric NO<sub>2</sub> concentration. Conversely, the sensitive oligotrophic species and the foliose broad-lobed species were significantly correlated with green spaces area and NDVIb. Crustose lichens showed the best correlations with NO<sub>2</sub> atmospheric concentration. Although many metrics responded to the environmental variables, following the parsimony principle, the higher and simple associations were considered. Thus, only richness, LDVt and FR were chosen for further analyses. Biplots of the selected lichen diversity metrics Richness, LDVt and FR against the most correlated environmental variables (NO<sub>2</sub>, Area and NDVIb) are shown in figures 6, 7 and 8.

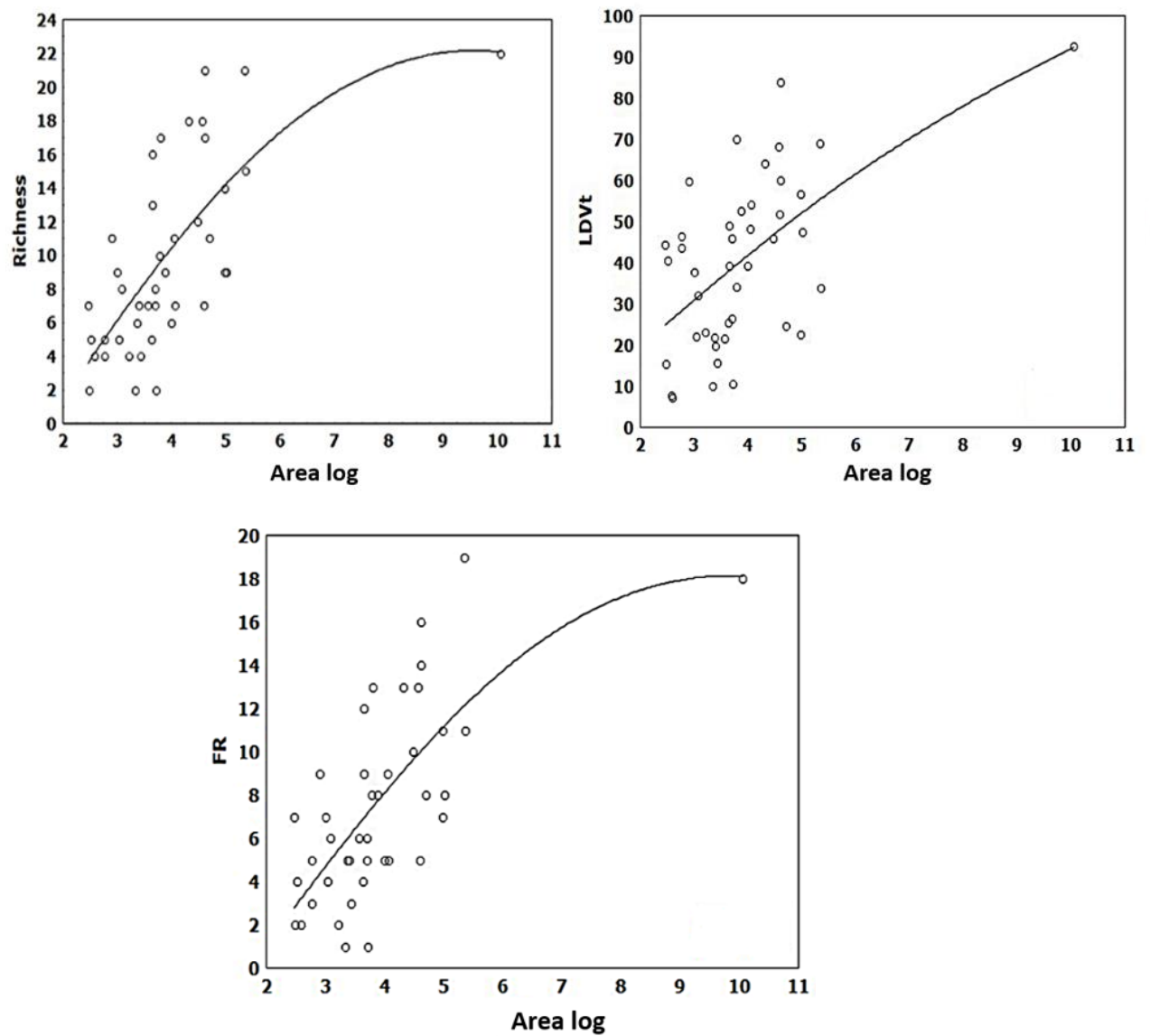
The environmental variables showed to be significantly correlated with several lichen biodiversity metrics (Table 3). Spearman correlations with the remaining environmental variables are shown in appendix IV. Slope, potential solar radiation (PSR) and distance to the coast (Dist) were not significantly correlated with lichen biodiversity metrics (appendix IV). Conversely, altitude was positively associated with most lichen biodiversity metrics. Tree diameter at breast height (DBH) was negatively correlated with almost all metrics. The area of green spaces (Arealog) and the classes of NO<sub>2</sub> concentrations (NO<sub>2</sub>) showed to be highly associated with the biodiversity metrics, but the area positively whereas NO<sub>2</sub> classes association was negative. Both NDVI inside and in the surrounding buffer and NDVI in the centroid of the green space (NDVIb and NDVIc, respectively) were significantly correlated with lichen biodiversity metrics. However, since NDVIb showed the most significant correlations and was highly correlated with NDVIc, further analyses considered only the NDVIb. Several buffer distances (50, 100 and 200 meters) around green spaces were tested to assess the effect of urban density. The 50 meters buffers (U50) showed the best correlation (100 and 200 meters buffer data shown in the appendix IV). From these set of variables, the best ones were considered for model construction: Alt, Arealog, NDVIb, NO<sub>2</sub> and U50 (Table 3).

**Table 3.** Spearman correlation coefficients between environmental variables and lichen biodiversity metrics. Environmental variables: Alt (altitude), Arealog (green space logarithmized area), U50 (urban density in 50 m buffer surrounding the green space), NO<sub>2</sub> (NO<sub>2</sub> atmospheric concentration) and NDVIb (NDVI in the green space and the 100m surrounding buffer). Lichen biodiversity metrics: Richness (species richness), FR (functional richness), LDVHygro (hygrophytic), LDVmesohygro (mesohygrophytic), LDVxero (xerophytic), LDVnitro (nitrophytic), LDVmeso (mesotrophic); LDVvoligo (oligotrophic); LDVcru (crustose); LDVfoln (foliose narrow), LDVfolb (foliose broad), LDVfrut (fruticose), LDVsq (squamulose), LDVlepr (leprose). Significant correlations are marked with an \*: \* =  $p < 0,05$ ; \*\* = at  $p < 0,01$ ; \*\*\* =  $p < 0,001$ . N = 42.

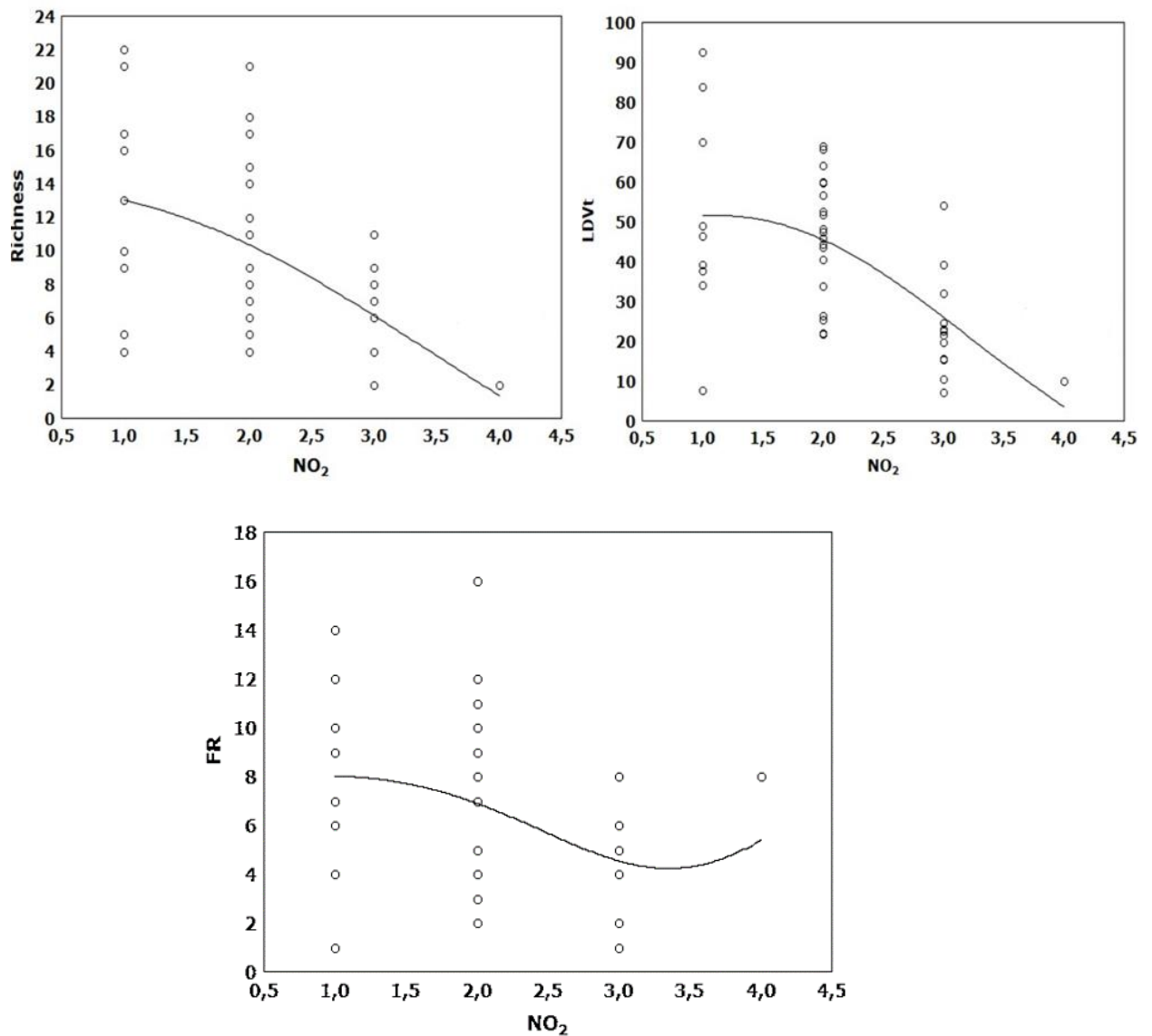
	<b>Alt</b>	<b>Arealog</b>	<b>U50</b>	<b>NDVIb</b>	<b>NO<sub>2</sub></b>
<b>Richness</b>	<b>0,454</b> **	<b>0,702</b> ***	<b>-0,366</b>	<b>0,778</b> ***	<b>-0,498</b> ***
<b>FR</b>	<b>0,427</b> **	<b>0,671</b> ***	<b>-0,418</b>	<b>0,758</b> ***	<b>-0,511</b> ***
<b>LDVt</b>	<b>0,454</b> **	<b>0,528</b> ***	<b>-0,584</b>	<b>0,701</b> ***	<b>-0,529</b> ***
<b>LDVnit</b>	0,051	0,005	<b>-0,406</b>	0,143	-0,272
<b>LDVmes</b>	<b>0,468</b> **	<b>0,557</b> ***	<b>-0,599</b>	<b>0,716</b> ***	<b>-0,501</b> ***
<b>LDVvolig</b>	<b>0,443</b> **	<b>0,592</b> ***	<b>-0,372</b>	<b>0,740</b> ***	<b>-0,397</b>
<b>LDVHygr</b>	<b>0,499</b> ***	<b>0,482</b> **	<b>-0,382</b>	<b>0,558</b> ***	<b>-0,464</b>
<b>LDVmesh</b>	<b>0,427</b> **	<b>0,641</b> **	-0,290	<b>0,681</b> ***	-0,230
<b>LDVxer</b>	-0,026	-0,007	<b>-0,401</b>	0,076	-0,209
<b>LDVcrust</b>	<b>0,344</b> *	<b>0,372</b> *	<b>-0,632</b>	<b>0,552</b> ***	<b>-0,530</b> ***
<b>LDVfoln</b>	0,077	-0,039	<b>-0,414</b>	0,110	-0,245
<b>LDVfolbr</b>	<b>0,467</b> **	<b>0,754</b> ***	-0,300	<b>0,773</b> ***	-0,175
<b>LDVfrut</b>	0,256	<b>0,416</b> **	-0,051	<b>0,409</b> **	-0,277
<b>LDVsq</b>	0,214	0,178	-0,152	0,233	<b>-0,311</b>
<b>LDVlepr</b>	<b>0,422</b> **	<b>0,433</b> **	-0,172	<b>0,492</b> **	-0,245



**Figure 6.** Selected lichen diversity metrics plotted with NDVIb (NDVI of the green spaces and the 100 meters buffer). Lichen diversity metrics: species richness (Richness), total lichen diversity value (LDVt) and functional richness (FR). The line was included to represent the shape of the relationship and was done using a smoothing function (Distance Weight Least Squares) with a 0.65 stiffness.



**Figure 7.** Selected lichen diversity metrics plotted with green spaces area (Area log, logarithmized area). Lichen diversity metrics: species richness (Richness), total lichen diversity value (LDVt) and functional richness (FR). The line was included to represent the shape of the relationship and was done using a smoothing function (Distance Weight Least Squares) with 0.65 stiffness.



**Figure 8.** Selected lichen diversity metrics plotted with NO<sub>2</sub> atmospheric concentration ( $\mu\text{g}/\text{m}^3$ ; NO<sub>2</sub> concentration values are grouped in class 1:  $>35 \mu\text{g}/\text{m}^3$ ; class 2:  $30 - 35 \mu\text{g}/\text{m}^3$ ; class 3:  $20 - 30 \mu\text{g}/\text{m}^3$ ; class 4:  $< 20 \mu\text{g}/\text{m}^3$ ). Lichen diversity metrics: species richness (Richness), total lichen diversity value (LDVt) and functional richness (FR). The line was included to represent the shape of the relationship and was done using a smoothing function (Distance Weight Least Squares) with a 0.65 stiffness.

### 3.4 Lichens richness model for green spaces

Several models were built for the estimation of lichens richness in urban green spaces using the set of previously selected environmental variables and

lichen diversity metrics (section 3.2 Lichen functional diversity metrics), using GLM (Generalized linear models). The identify link was used because all relationships approached a linear shape. Models with green space area as variable could not be satisfactorily fitted using these model specifications, due one sampling site that had a much higher area than the others (site Monsanto). Thus, this site was excluded from the models. Without it, the relationships with area were linear. Lichen diversity value and species richness air quality models showed similar results. For this reason, only the models for species richness are shown. After running all possible combinations, only the five models with higher AICs were selected and are detailed in table 4. The parsimony principle was applied in model selection. From the five models, those with at least one non-significant variable were discarded. The best model was then selected based on the highest AIC value for the lowest number of variables (Table 5). The final model explaining lichen species richness in the study area included Area and NO<sub>2</sub> (AIC = 216,827; p < 0,001). The model equation obtained was the following:

Model: **Richness = 0,461-3,174NO<sub>2</sub>+4,15Area**

**Table 4.** Summary of the Generalized Linear Models (GLMs) explaining the effects of environmental variables on lichen species richness. Only the five models with higher AICs, and its significance value are shown. NO<sub>2</sub> (class of NO<sub>2</sub> atmospheric concentration), NDVIb (NDVI in the green space and in a 100 m buffer surrounding the green space), Arealog (logarithmized green space area), U50 (urban density in 50 m buffer surrounding the green space). Number of observations = 41. Symbol (\*) indicates the selected model.

Variables	AIC	P value
<b>NO<sub>2</sub> ; DBH ; Area ; NDVIb</b>	215,031	< 0,001
<b>Area ; NDVIb ; NO<sub>2</sub></b>	215,708	< 0,001
<b>NO<sub>2</sub> Area, DBH, NDVIb, U50</b>	216,139	< 0,001
<b>NO<sub>2</sub> ; Area (*)</b>	216,826	< 0,001
<b>NO<sub>2</sub> ; Area ; NDVIb ; U50</b>	217,089	< 0,001



**Table 5.** Regression results obtained by a generalized linear model explaining lichen species richness using green spaces area and class of NO<sub>2</sub> atmospheric concentration. The values given are the predictor's estimates. Standard errors are shown in parenthesis. Predictor variables: NO<sub>2</sub> (Classes of NO<sub>2</sub> concentrations (µg/m<sup>3</sup>)); Arealog (green spaces logarithmized area (m<sup>2</sup>)).

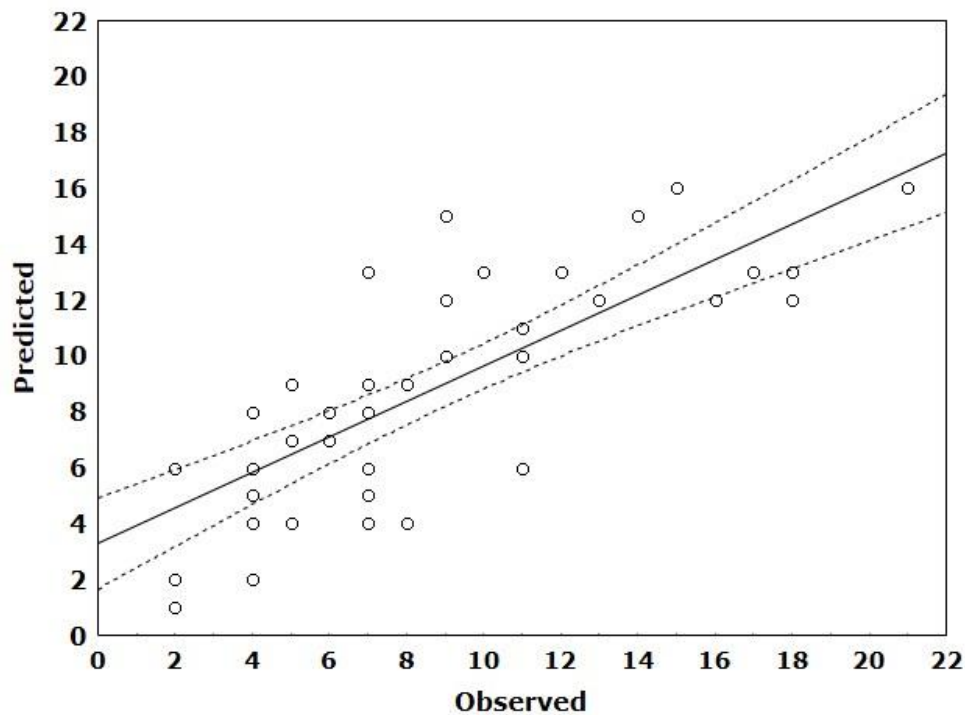
Effects	Model
<b>Intercept</b>	0,461 (2,675)
<b>NO<sub>2</sub></b>	-3,174 *** (0,642)
<b>Arealog</b>	4,15 *** (0,592)
<b>No. of observations</b>	<b>42</b>

The effect of interactions between variables was tested and the results showed that there was no significant interaction (data not shown). Results of cross validation performed for the model are shown in table 6. A tendency for underestimating maximum values was observed, but the average and median predicted values fitted well the observed ones. Plotting the observed versus predicted values showed a small tendency for overestimation of the number of species in sites with less species (Figure 9).

**Table 6.** Statistics for the observed and predicted values obtained by cross-validation of a generalized linear model explaining lichen species richness using green spaces area and class of NO<sub>2</sub> atmospheric concentration. Error

average was determined calculating the modulus of the difference between the observed and the predicted values.

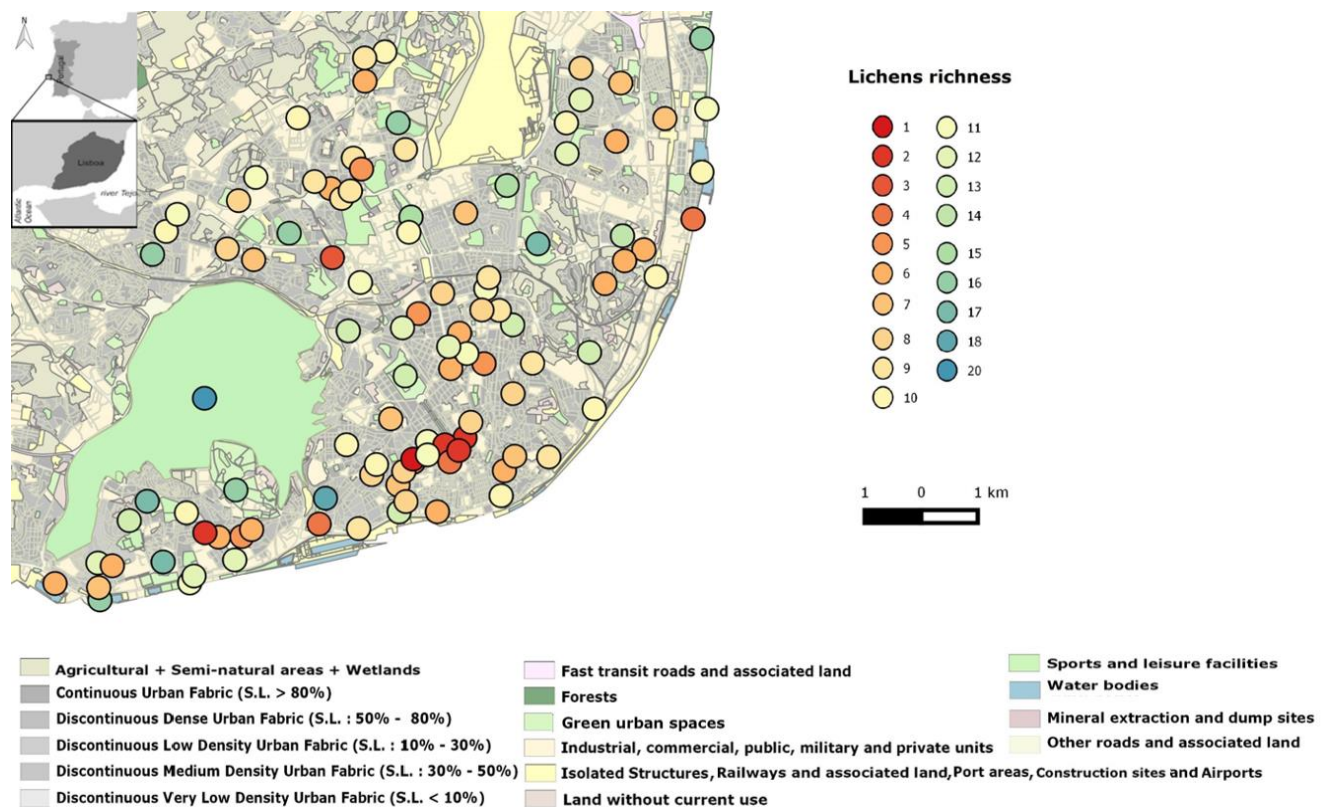
	<b>Predicted values</b>	<b>Observed values</b>
<b>Average</b>	9,171	9,195
<b>Coefficient of Variation</b>	45,80	57,146
<b>Max</b>	16	21
<b>Min</b>	1	2
<b>Median</b>	9	8
<b>Standard Deviation</b>	4,201	5,255
<b>Error average</b>	2,683	



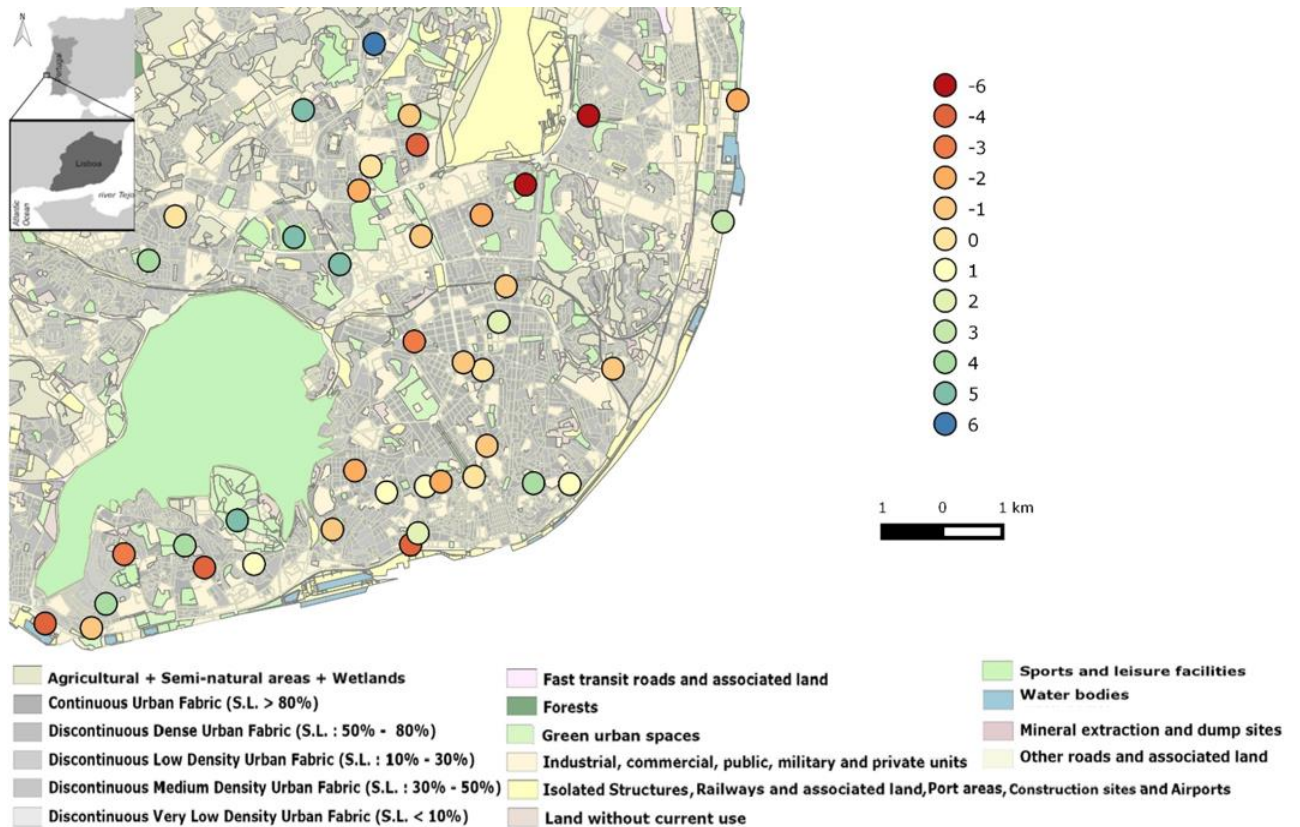
**Figure 9.** Predicted values of a generalized linear model explaining lichen species richness using green spaces area and class of NO<sub>2</sub> plotted with the observed values. This was performed on 10 subsamples of approximately 10% randomly chosen values. Regression bands with 95% confidence level are shown.

### 3.5 Applying the lichens species richness model to other green spaces

The model developed previously was used to estimate lichen species richness for other Lisbon green spaces. Results show that lichen species richness is lower in the center-south of the city, as already seen from sampled lichen diversity (figure 10).

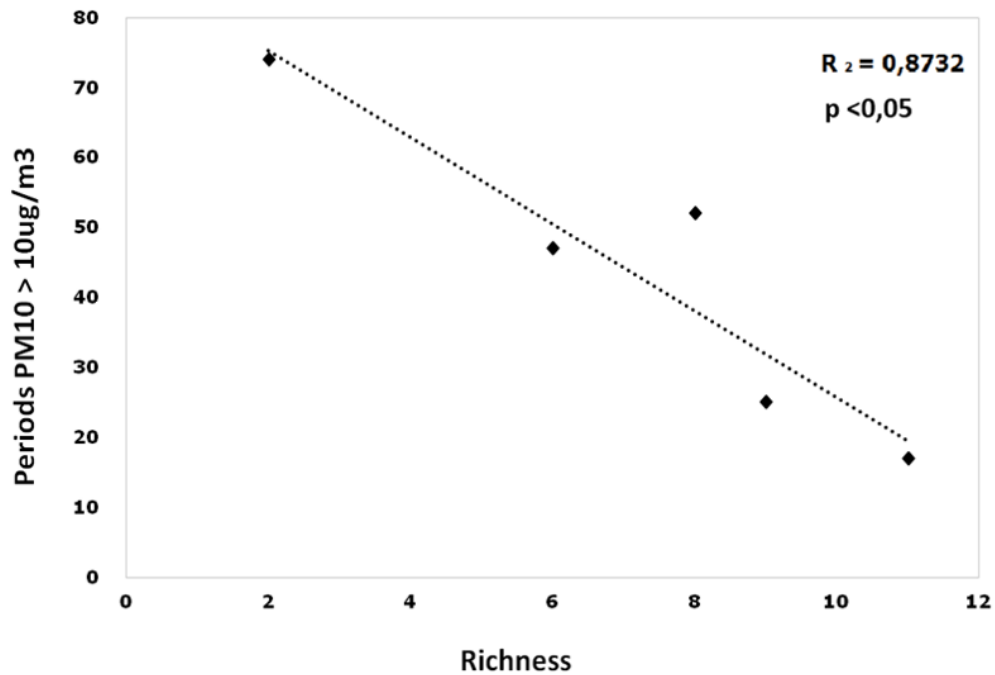


**Figure 10.** Land-use map of Lisbon. Colored circles represent estimated lichen species richness ranging from low (red) to high (blue) for each green space of the city.



**Figure 11.** Land-use map of Lisbon. Colored circles represent model residuals.

As estimated values were slightly biased, residuals of the estimates of lichen species richness were plotted to understand its spatial distribution. The analysis of the residuals map shows that the areas immediately south and SE of the airport lichen diversity values are overestimated when compared to the observed values. The center of Lisbon corresponds to the area where the model more accurately reflects the observed values (Figure 11).



**Figure 12.** Number of periods (20 consecutive measurements) with PM<sub>10</sub> equal or above 10ug/m<sup>3</sup> measured in the air quality stations located in Lisbon during 2013 (Periods PM<sub>10</sub> µg/m<sup>3</sup>) plotted with the number of lichen species (Richness) observed in the smallest green spaces (< 1 ha) closest to each air quality station. R<sup>2</sup> represents Pearson correlation coefficient.

We compared the number of lichen species close to the existent air quality monitoring stations in Lisbon measuring PM<sub>10</sub>. Despite the low number of stations, lichen diversity showed to be significant linearly correlated with the number of periods with PM<sub>10</sub> above 10ug/m<sup>2</sup> during 20 consecutive measurements (Figure 12).

With a 10% increase in green spaces area, those with smaller size show higher percentage of lichen species richness increase than green spaces with larger area. When the concentration of NO<sub>2</sub> is higher the increase of the number of lichen richness, with the 10% increase of area, is greater than with lower NO<sub>2</sub> concentration (Table 7; Plot is shown in appendix V).

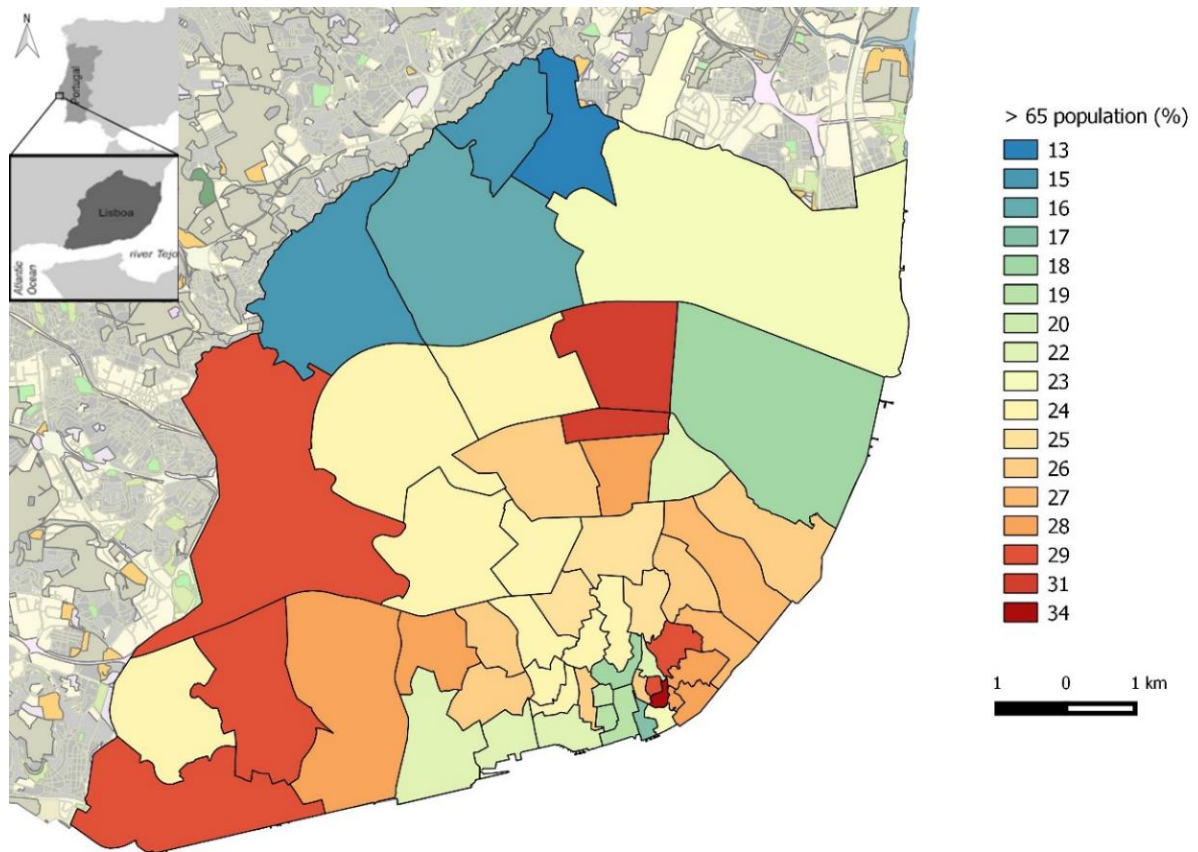
**Table 7.** Effect of 10 % increase of green spaces area in lichens species richness. Area (green spaces area, m<sup>2</sup>), NO<sub>2</sub> (classes of NO<sub>2</sub> concentration, class 1: >35 µg/m<sup>3</sup>; class 2: 30 - 35 µg/m<sup>3</sup>; class 3: 20 - 30 µg/m<sup>3</sup>; class 4: < 20 µg/m<sup>3</sup>).

Area	NO <sub>2</sub> = 1	NO <sub>2</sub> = 2	NO <sub>2</sub> = 3
300 m <sup>2</sup>	2,3%	3,9 %	14,1%
1000 m <sup>2</sup>	1,7%	2,6%	5,1%
50000 m <sup>2</sup>	1,0%	1,3%	1,6%

### 3.6 Risk maps for health problems associated with air quality

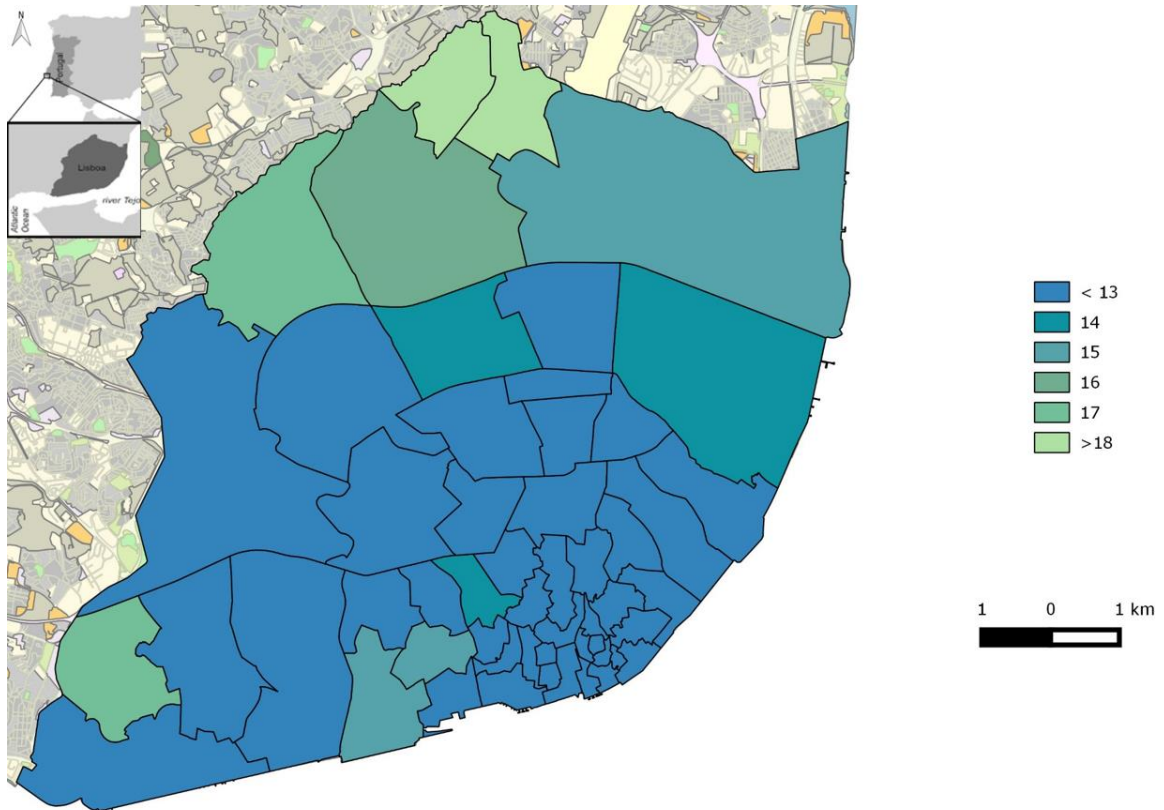
Since not all the population has the same vulnerability to air pollution, maps of each vulnerable population group by parish were first created. In the east part of the city, the proportion of citizens belonging to the group of population over 65 years is higher. The parish with lower percentage of elderly people is located in the northern area whereas the one with the highest percentage of elderly population is located in the city center (Figure 13).

The other vulnerable group of the population is children (< 14 years old). The parishes with higher percentage of children are located in the north of Lisbon (Figure 14).



**Figure 13.** Map of Lisbon showing the percentage of population over 65 years old by municipality subdivision (municipality subdivision). Colors represent classes of percentage. Map is based on information obtained from the Census 2011.

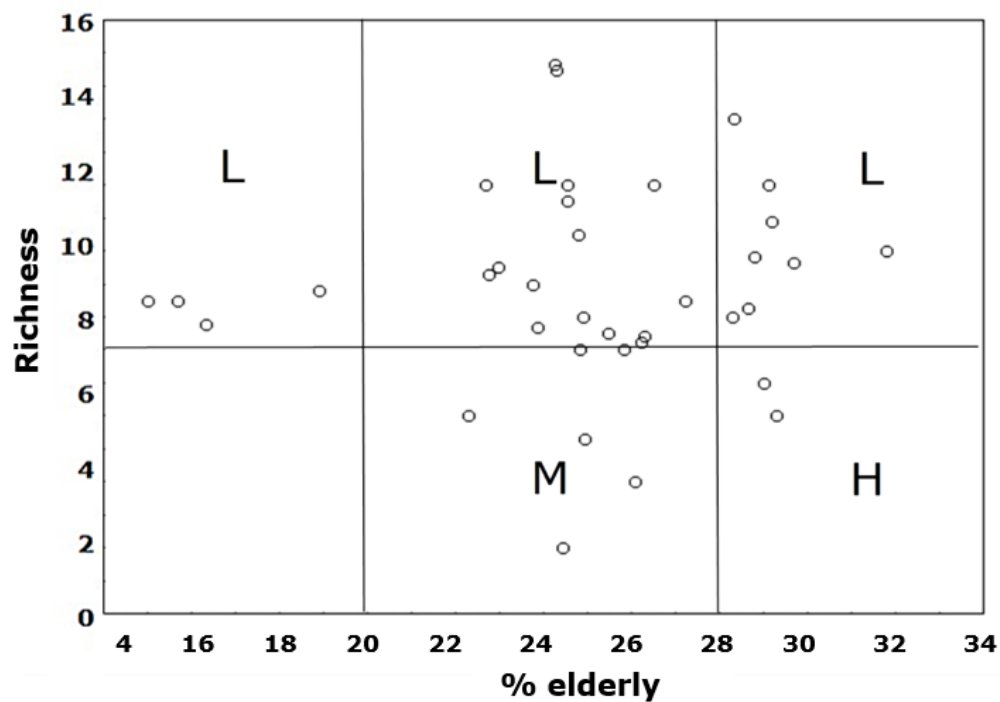




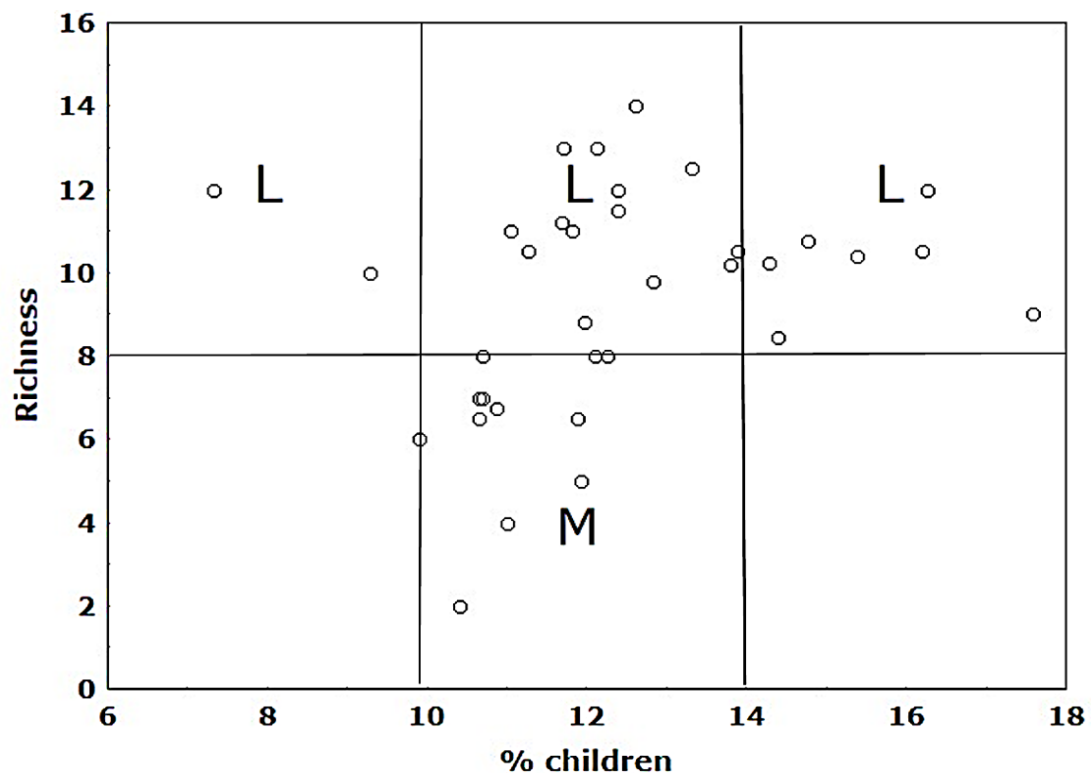
**Figure 14.** Map of Lisbon with the percentage of population under 14 years old by municipality subdivision. Colors represent classes of percentage. Map is based on information obtained from the Census 2011.

The potential risk of each parish was obtained accounting with the proportion of elderly or younger population and mean lichen species richness estimated for green spaces at each subdivision (Figure 15 and 16, respectively). Considering the elderly population, two city subdivisions show a high risk: Castelo and Graça. On the other hand, 6 city municipality subdivisions were classified as medium risk, Anjos, Encarnação, Mercês, Pena, São José and São Paulo.





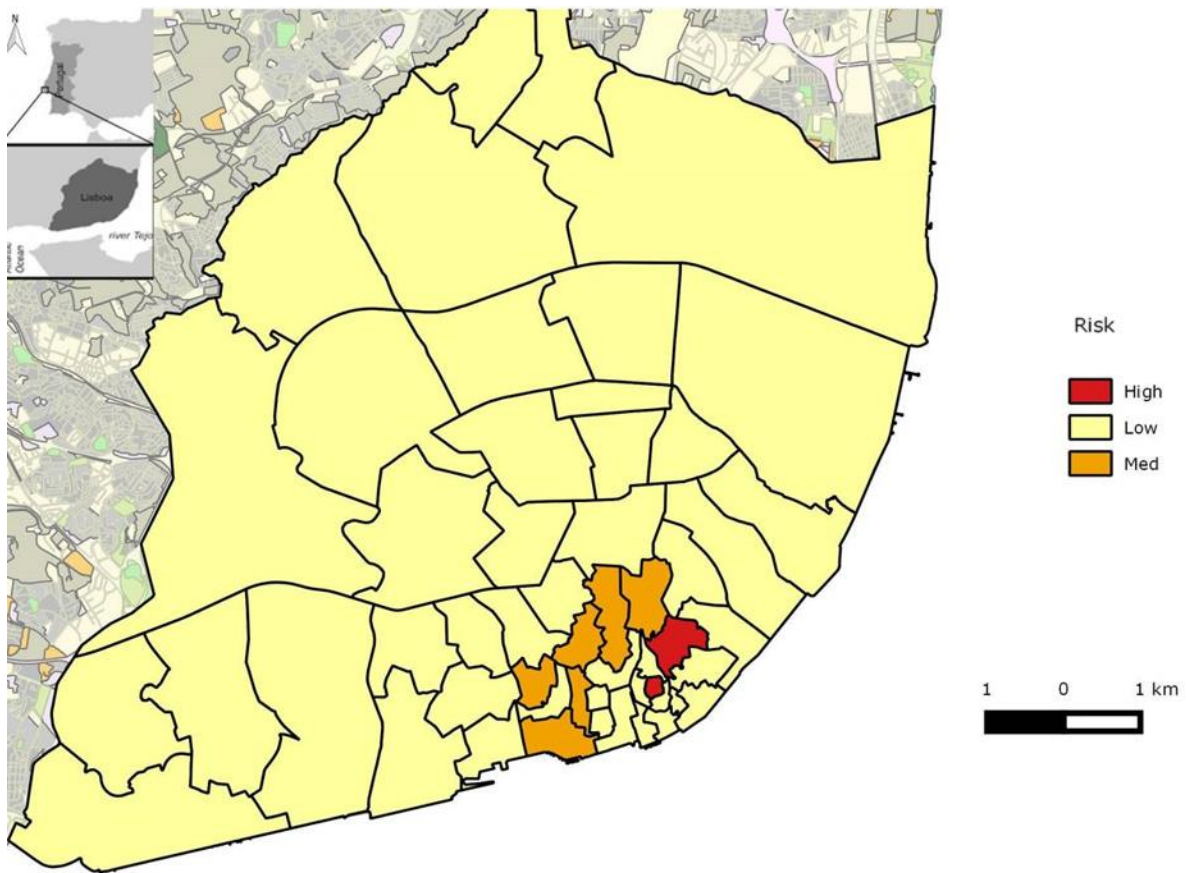
**Figure 15.** Average lichen species richness estimated for Lisbon at the parish level (Richness) plotted with the percentage of elderly people (>65 years old) in the same subdivision (% elderly). Letter L represents low risk parishes, M represents medium risk and H represents high risk parishes.



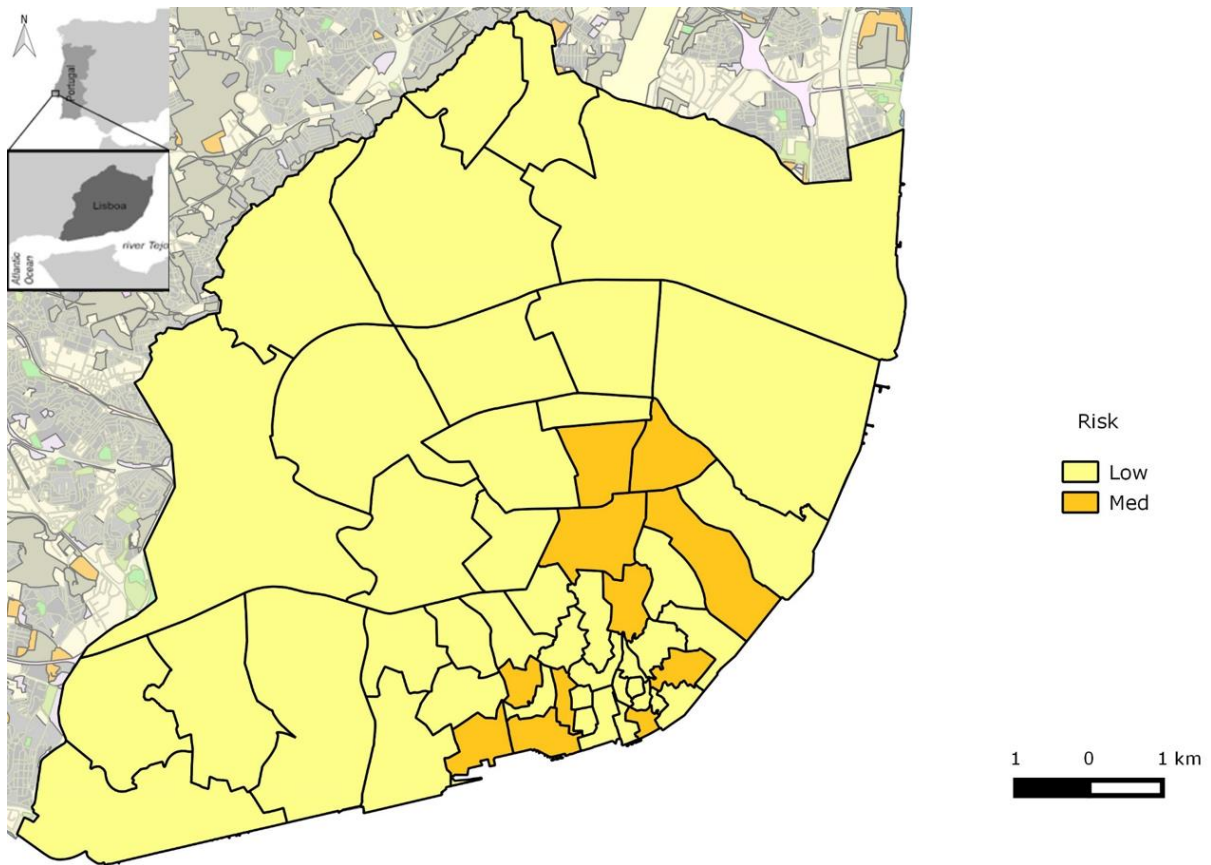
**Figure 16.** Average species richness estimated for Lisbon at the parish level (Richness) plotted with the percentage of younger population (0-14 years)

old) in the same municipality subdivision (% children). Letter L represents low risk parishes, M represents medium risk and H represents high risk parishes.

The health risk maps obtained for Lisbon elderly and younger population are shown in figures 17 and 18, respectively. For both vulnerable population groups, the highest risk is always in the center-south of the city.



**Figure 17.** Health risk map for elderly people (> 65 years old) by parish. High corresponds to a high risk areas, Med corresponds to medium risk areas and Low corresponds to low risk areas.



**Figure 18.** Health risk map for children (< 14 years old) by parish. Med corresponds to medium risk areas and Low corresponds to low risk areas.

## 4. Discussion

### 4.1 The patterns of lichen diversity in Lisbon green spaces

Lichen species richness in Lisbon's green spaces varied substantially from site to site (from 2 to 22 lichen species). From 1978 to 1984, a lichen and bryophyte assessment was developed in the southern part of the Tagus Estuary and included also Lisbon (Sérgio et al., 1985). In this study, the number of lichen and bryophyte species in the center-south of Lisbon ranged from 0 to 4, while in the Western and Northern areas of the city lichen species varied from 35 to 50 species per site (Sérgio et al., 1985). Works in other

European cities showed similar current species richness ranges in urban areas, but with a more marked trend of increase in species richness over time. In London, a work performed in 2004 showed that the number of lichen species per site varied from 8 to 25 (Davies et al., 2007), whereas in the 70's the number of lichen species in that city varied only between 0 and 7 (Davies et al., 2007). Also in the Finish city of Tampere the number of lichen species increased from a range of 0 to 7 in 1980, to 3 to 14 species in 2000 (Ranta, 2001). Like species richness, also the pattern of LDVt found in Lisbon green spaces varied among sites, ranging from 7,25 to 83,75. This pattern of variation is also similar to that found in Central London (8,6 - 76,9 ; Larsen et al., 2006) or in a small Portuguese city (c.15 to 60; Llop et al., 2012).

The range of air quality we observed in Lisbon is comparable to that of London (a larger city) and to a smaller city in Finland (Davies et al., 2007; Ranta, 2001; Larsen et al., 2006) and Sines (Llop et al., 2012). This suggests that these patterns of considerable variation of lichen species richness and LDVt in urban areas are generalized, and that the pattern is not exclusive to large cities. These cities' heterogeneity in terms of air pollution highlights the need for maps with high spatial resolution for informed management decisions can be made. The temporal trends of air pollution in cities suggest the importance of the background air pollution component, in addition to the important role of current local sources of pollution. A substantial increase in the number of lichen species was observed from the 70's or 80's to the present time in European cities (Davies et al., 2007; Ranta, 2001). In Lisbon, this air quality improvement was not so apparent. Our results from the center-south parts of Lisbon suggest a similar air quality to that assessed by Sérgio et al. (1985) in the 70's. On the other hand, in the 70's the air quality seemed to be better in Western and Northern areas than in present day, as shown by the higher number of lichens and bryophytes observed then. These temporal patterns can be explained by several factors. Since the 70's the city expanded to some areas that had quite reasonable air quality, areas that were probably closer to green spaces in the past. The worsening of conditions observed by us in 2015 may probably be due to land use change, resulting from the conversion of green spaces to constructed areas. Moreover, the higher number of lichens and bryophytes observed in the 70's might not be so directly comparable to

that sampled by us. Numbers might be biased: 1) by the fact that they account with both groups together; 2) the sampling methodology was different back then and included the visualization of the whole tree trunk and branches, in opposition to the method used by us that inspects only a small area at breast height. In addition to these factors, Portugal was not so highly industrialized as were most European countries in the 70's and 80's, nor did the levels of charcoal combustion for house heating in Portugal closely resembled other European regions. The industrialization started later in Portugal and with cleaner technologies. This could have probably influenced Lisbon air quality, which had probably less sulphur dioxide and particles than most other European capitals during the 70's and 80's. In fact, the maximum values of diversity in other European cities in the 70's were considerably lower than that observed in Lisbon (Davies et al., 2007; Ranta, 2001; Sergio et al., 1985). Also, the increase in the number of vehicles from the 70's to present day occurred simultaneously with less emissions per vehicle due to cleaner technologies, justifying the apparent maintenance of the same ranges of air quality in Lisbon.

In this work Xerophytic and Nitrophytic lichens were the most abundant functional groups, together with foliose narrow and crustose growth forms. Also in London a higher abundance of nitrophytic lichens was reported (Davies et al., 2007). These results can be supported by the fact that cities are associated with high nitrogen concentrations both NO<sub>x</sub> and NH<sub>3</sub> (Svirejeva-Hopkins et al. 2011). Moreover, due to the urban heat island effect the temperature is higher and the relative humidity is lower, particularly in the center of the city (Oke, 1987). Fruticose lichens were the least abundant. This is probably related to their sensitivity to air pollution, since this functional group is regarded as the most sensitive to air pollution due to its large surface area of exposure to atmosphere (Awasthi 2000).

The oligotrophic lichen functional group was the most correlated with the area of green spaces and the NDVI<sub>b</sub>. At the same time, oligotrophic species were negatively associated with anthropogenic pressure measure here by NO<sub>2</sub> atmospheric concentration which is used here as a surrogate traffic intensity and thus of air pollution in cities caused by traffic (Ito et al., 2007; Moldanová et. al, 2011), because it is usually one of the easiest to measure and map at

a high spatial resolution, in opposition to particles or SO<sub>2</sub>, for instance. In our case, NO<sub>2</sub> atmospheric concentration was used because it was the only pollutant available with a relatively good spatial resolution. This pollutant is known to have high deleterious effects on lichens under controlled conditions at concentrations two orders of magnitude higher (c. 6 mg/m<sup>3</sup>) (Nash III, 1976) than those found currently in Lisbon (<4 µg/m<sup>3</sup>). The negative relation found between NO<sub>2</sub> concentration and the oligotrophic lichens suggests that this relationship is in fact reflecting the effects of other pollutants usually emitted together with NO<sub>2</sub> which are known to affect lichens for concentrations closer to the ones observed in urban areas such as SO<sub>2</sub> and particles (Showman, 1972). A recent work exposed lichens to diesel exhaust under controlled conditions and showed that lichens were affected by the mixture of pollutants present although they were not able to separate the individual pollutants effects (Langmann et al., 2014). A work from Pinho and co-workers (2008) showed the high sensitivity of oligotrophic lichen species to general increased levels of pollutants in a multipollutant area. This group sensitivity was also demonstrated in small cities, as their abundance was lower in areas near roads, when compared to parks and residential areas (Llop et al., 2012).

Lichen species richness was the biodiversity metrics that best performed in response to the environmental variables and, thus, the one selected to be used as a surrogate of air quality and for model construction. This metric is a simple and very intuitive measure that can be easily communicated for general public and stakeholders as an air quality measure. Other metrics including the ones that have in account cover of species (LDVt) and functional richness (FR) gave similar results but we decided to use a simple and intuitive biodiversity metrics the number of lichen species.

## **4.2 Factors affecting air quality in green spaces**

Most lichen diversity metrics tested showed correlations with the environmental factors. In general, an increase in the green space area lead

to an increase in species richness, LDVt and the LDV of functional groups, except for the most tolerant functional groups in terms of water requirements and eutrophication (xerophytic and nitrophytic). Although we were able to observe some changes in the abundance of lichen communities and in lichen functional diversity, those were not as clear as the marked decline in the number of lichen species. In cities smaller than Lisbon, functional groups responded better than total diversity to gradients of environmental change from rural to urban areas induced by different land-use in urban areas (Llop et al., 2012; Munzi et al., 2014). In both cases moving closer to cities or closer to more disturbed sites had no strong effect in the number of lichen species, but induced changes in the community, with the most sensitive species being replaced by the tolerant ones (Munzi et al., 2014; Llop et al., 2012). The authors suggested the shift to a more nitrophytic community to be an effect of alkaline dust particles and/or atmospheric NH<sub>3</sub> emitted by traffic (Llop et al., 2012). On the other hand, the observed shifts to xerophytic dominated communities were suggestive of a heat island effect (Munzi et al., 2014). In our work we did not observe clear shifts in the communities, neither in relation to water requirements, nor in relation to eutrophication. This lack of clear communities' shifts together with the dramatic decrease in species richness are a clear indication that in Lisbon air pollution levels are still high enough to have a deleterious effects on the overall lichen community. Moreover, the lack of clear community shifts related to water requirements, suggests that the pollution driver still plays a more important role in the city than the heat island effect, due to its large size and traffic intensity. Thus, the main factor determining the distribution of lichen species in Lisbon is the level of air quality.

As expected lichens species richness decreased in areas with higher PM<sub>10</sub> concentrations, showing a high association between lichens species richness and air pollution. Our results suggest that PM<sub>10</sub> concentrations affect lichens richness, which is supported by other works (Langmann et al., 2014). Therefore, lichens species richness is used as a surrogate for air quality of green spaces.

We found that the most important factors explaining air quality in Lisbon green spaces were the size of the green space (Area), the tree density

(NDVIb) and the traffic intensity (concentration of NO<sub>2</sub>). Taking into consideration that we considered lichen species richness as a surrogate of air quality, thus an increase in lichen richness can be associated to an improvement in air quality. NDVIb was the most significant factor in relation with the lichen metrics, followed by Area and NO<sub>2</sub> respectively. Zupancic and co-workers' review (2015) suggested that vegetation density is the main responsible for the ecosystem service air purification in urban forests. Our results also suggest that air purification increases with green space area. In fact, a previous work showed that the size of the green space is important to reduce the penetration of air pollutants (Ali, 2013). Moreover, some pollutants, such as particulate material have short deposition distances (<500m). This along with tree leaves roughness make it more difficult to particles to reach the central area of a green space (Gheorghe & Ion, 2011). Thus, our work reinforces from an ecological indicator perspective the important role that size and tree density of cities' green spaces have in providing the service air purification. This represents an innovation of this work, in the sense that it tackles simultaneously a large range of green space sizes together with ecological indicators evaluation.

Other factors were also found to be associated with lichen species richness. However, they were likely associated to the green space area, tree density or the concentration of NO<sub>2</sub>, providing no extra explanation for understanding the patterns of lichen species richness patterns. The type of matrix around each green space was relevant, with the proportion of area covered by urban density around each green space negatively influencing the air quality in its center. Similar results were also observed in the smaller city of Almada showing that the urban density matters for the effects of the urban heat island effect (Munzi et al., 2014). The results also show a significant positive association of air quality with increasing altitude. Valleys channel air flow and frequently "trap" polluted air originating high pollutant concentrations at lower altitudes (Falke & Schichtel, 2000). Lisbon city center is associated with a valley (Alcoforado, 2009) and, as seen in our work, has higher air pollution (seen with the surrogate NO<sub>2</sub> concentration).



Environmental variables more related to microclimatic conditions, such as slope, distance from the coastline and PSR, did not show a significant association with green spaces air quality. This supports our conclusion that air quality is the main factor affecting lichen metrics, rather than other factors related with microclimate. These factors can influence lichens (e.g. by favoring hygrophytic lichens in areas more protected from the sun, with lower PSR values, Pinho, 2010), but this is only visible when atmospheric pollution is found at lower levels than those found in Lisbon.

Interestingly, some green spaces revealed large deviations between the observed and predicted values. These green spaces are mostly located near the airport. The variable that we used as surrogate of vehicle traffic is NO<sub>2</sub> modeled for the city of Lisbon in only 4 classes and for 2001. Some changes might have occurred during this period namely the substantial increase in air traffic close to the airport during the last years. Further work is necessary here to evaluate the real impact that the airport traffic has on the surrounding area.

#### **4.3 The role of Lisbon gardens in air purification**

Green spaces in the city clearly showed to provide air purification service but how much can we rely on them for improving air quality? In the same region with the same background pollution level, a green space area increase of 10% has a much higher effect in small green space located in polluted areas than in larger ones located in cleaner areas of the city. For instance, a green space with 300 m<sup>2</sup> of area has a 14,1% increase air purification service while one with 50000 m<sup>2</sup> has only a 1,3% increment, in a NO<sub>2</sub> concentration of 20 – 30µg/m<sup>3</sup> (class 3). Because lichen species richness seem to vary linearly with one of the main components of urban air pollution, which are dust particles, we can assume that air quality also improved linearly with the increase in the number of lichen species.

It is important to note that the relationship between the area of a green space and species richness is not linear, but rather logarithmic (note that area was log prior to modeling, thus resulting in a linear relationship for the model).

As a consequence, the establishment of small gardens, or the increase of area in small ones, will result in a large gain of air quality improvement, when compared to building large gardens or increasing those already large. This effect would be especially relevant in very dense urban areas, where the existing green spaces are few and small and no space is available for larger green spaces. One important result of the model was to show that extremely large green spaces (Monsanto, ~1000ha) do not hold many more species than the very large ones (e.x. Parque Bensaude ~22ha). In fact both sites present a similar number of species (c. 20), which likely corresponds to the background maximum number of species per site in the region. Thus, increasing the area of a green space above 10ha is probably not going to cause any further increase in local air quality.

As expected, in the city center-south air quality of green spaces is low there are high density of urban areas (with buildings occupying about 50% of the total floor area) and green spaces are conspicuously absent (Alcoforado et al., 2009).

#### **4.4 Air quality in Lisbon: focusing on risk areas for humans**

In this work a health risk map was built for Lisbon parishes. The city center-south is where air quality is worse and, thus, where the resident population is at higher risk. In this area, air pollution in green spaces is worse and the percentage of elderly people is higher, thus resulting in a higher risk area for this population group. The younger population lives mostly in parishes further away from the city center, thus with better air quality, which results in a lower risk for this susceptible group.

Considering the lack of green spaces with larger areas in the center of the city and the percentage of elderly people in some parishes, this is an area that requires special attention. A mitigation measure could be the construction or increase of small green spaces, which would have a large impact in this area as previously explained. If not possible, increasing tree density in the existing green spaces should be considered. As air quality in

an urban green spaces improved with increasing vegetation density, the readjustment of the existing green spaces by planting additional trees, can be an alternative. Green roofs, green walls and increasing the number of trees and shrubs on road sides are other options that can be implemented.

As expected air pollution driver by traffic intensity (e.g. seen using NO<sub>2</sub> or particles as surrogates) determined air quality of urban green spaces (seen using lichen species richness as a surrogate). Given the relationship of e.g. particulate matter with health, any direct measures to decrease air pollution would result in a direct gain in air quality, and should be considered together with the precious suggested measures. Close car traffic on roads, decrease traffic in the city center by restricting non-electric cars circulation in some streets and reducing the traffic by changing roads with two ways by just one are examples of these direct measures.

## **5. Final remarks**

This work suggests that atmospheric pollution is the preponderating factor affecting lichen diversity in Lisbon. As a consequence, total diversity metrics like species richness responded better to the predominant environmental factors than functional diversity, thus being the best ecological indicator of air quality for Lisbon green spaces. Further work should be done to evaluate the impact of atmospheric pollution due to the Lisbon airport.

For the first time, we were able to map air quality in more than 100 green spaces in Lisbon. The map was based on a model of air quality evaluated through an ecological indicator, using Area and NO<sub>2</sub> concentration as the explaining variables. This represents also an innovation, in the sense that it tackles simultaneously a large range of green space sizes together with ecological indicators evaluation, something that is innovative. The best variables explaining air pollution reduction effect of urban green spaces were tree density, green space area and the NO<sub>2</sub> concentration. These results

highlight the importance of green spaces for providing the air purification service. The model built uses a small number of variables, an advantage that makes it easier to be applied.

A risk map was constructed concealing susceptible population distribution and green spaces air quality. The higher risk areas are located in the city centre, where elderly population is also more dense. This risk map can be applied by decision and policy makers to plan future city interventions. Considering the difficulties in increasing the number of green spaces or their size in the city center, due to the high urban density, it is suggested to increase tree density. Green roofs and green walls are also a good measure to go beyond these problems.

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# Appendices

## Appendix I

Sampled green spaces principal environmental variables and principal metric: Richness, sampled lichens richness; Area, green spaces area; NO<sub>2</sub>, Nitrate dioxide concentrations.

Green space	Richness	Area	NO <sub>2</sub>	Green space	Richness	Area	NO <sub>2</sub>
<b>1</b>	7	2,46	2	<b>22</b>	17	3,79	1
<b>2</b>	6	4,00	3	<b>23</b>	13	3,65	1
<b>3</b>	5	2,76	1	<b>24</b>	7	3,69	2
<b>4</b>	4	3,43	3	<b>25</b>	11	2,90	2
<b>5</b>	8	3,07	3	<b>26</b>	9	3,88	2
<b>6</b>	10	3,78	1	<b>27</b>	6	3,37	2
<b>7</b>	9	3,01	1	<b>28</b>	2	2,48	3
<b>8</b>	8	3,70	2	<b>29</b>	9	4,97	3
<b>9</b>	15	5,36	2	<b>30</b>	7	3,40	3
<b>10</b>	9	5,02	2	<b>31</b>	5	3,64	2
<b>11</b>	11	4,70	3	<b>32</b>	2	3,71	3
<b>12</b>	18	4,31	2	<b>33</b>	4	2,59	3
<b>13</b>	7	3,56	3	<b>34</b>	5	2,51	2
<b>14</b>	14	4,98	2	<b>35</b>	4	2,76	2
<b>15</b>	4	3,21	3	<b>36</b>	12	4,47	2
<b>16</b>	7	4,59	2	<b>37</b>	11	4,05	2
<b>17</b>	7	4,06	3	<b>38</b>	18	4,56	2
<b>18</b>	21	4,61	1	<b>39</b>	5	3,04	2
<b>19</b>	21	5,34	2	<b>40</b>	4	2,58	1
<b>20</b>	17	4,61	2	<b>41</b>	22	10,05	1
<b>21</b>	16	3,65	1	<b>42</b>	2	3,34	4

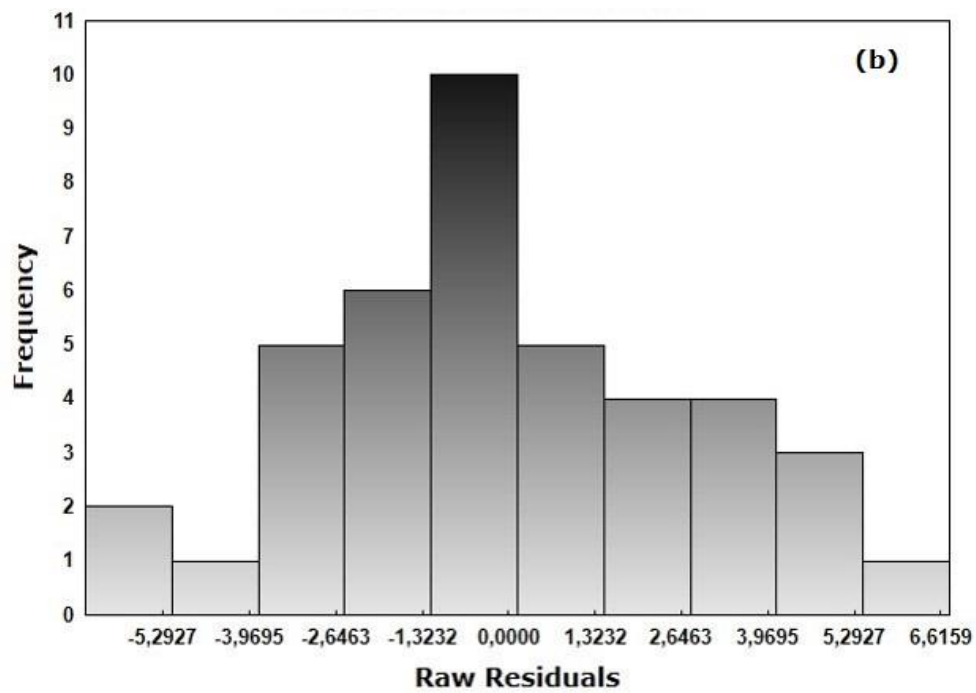
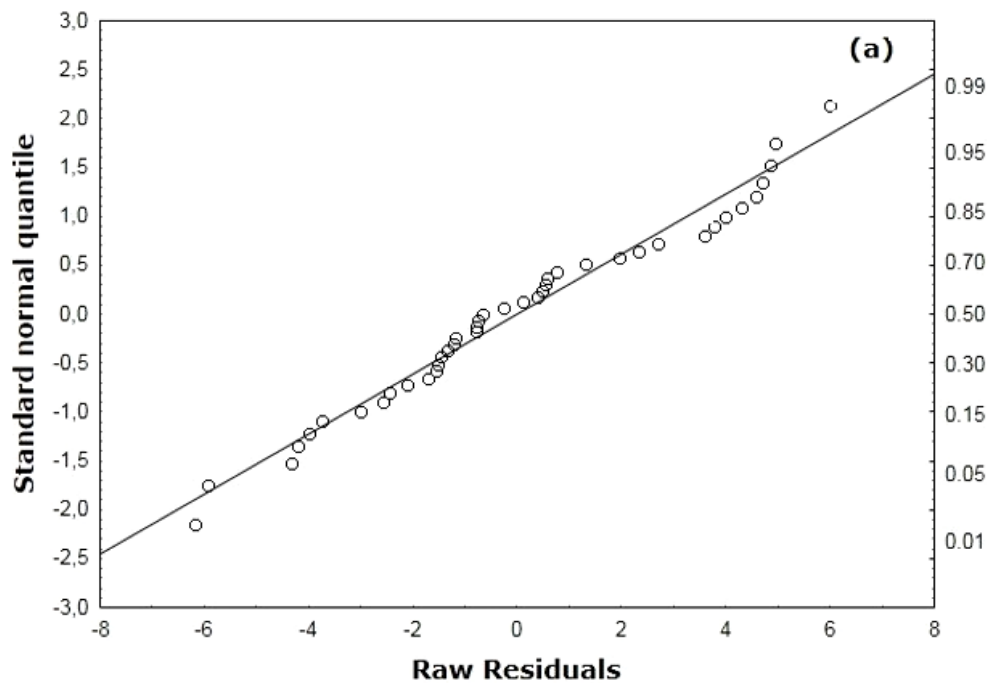
## Appendix II

List of species found in the total green spaces. Nomenclature follows Nimis & Martellos (2008).

<i>Candelaria concolor</i>	<i>Phaeophyscia orbicularis</i>
<i>Candelariella xanthostigma</i>	<i>Physcia adscendens</i>
<i>Caloplaca citrina</i>	<i>Physcia clementei</i>
<i>Chrysotrix candelaris</i>	<i>Physcia dubia</i>
<i>Diploicia canescens</i>	<i>Physcia leptalea</i>
<i>Evernia prunastri</i>	<i>Pyscia tenella</i>
<i>Enterographa crassa</i>	<i>Physcia tribacioides</i>
<i>Flavoparmelia caperata</i>	<i>Physconia grisea</i>
<i>Hyperphyscia adglutinata</i>	<i>Punctelia borreri</i>
<i>Lecania cyrtella</i>	<i>Ramalina lacera</i>
<i>Lecania cuprea</i>	<i>Ramalina farinacea</i>
<i>Lecania naegelli</i>	<i>Ramalina fastigiata</i>
<i>Lecanographa amylacea</i>	<i>Rinodina capensis</i>
<i>Lecanora chlarotera</i>	<i>Schismatomma decolorans</i>
<i>Lecanora expallens</i>	<i>Xanthoria parietina</i>
<i>Lecanora horiza</i>	<i>Waynea stoechadiana</i>
<i>Lecanora pulicaris</i>	
<i>Lecidella elaechroma</i>	
<i>Lepraria sp.</i>	
<i>Parmotrema hypoleucinum</i>	
<i>Parmotrema perlatum</i>	
<i>Parmotrema reticulatum</i>	
<i>Pertusaria amara</i>	
<i>Pertusaria pertusa</i>	
<i>Phaeophyscia endophoenicea</i>	
<i>Phaeophyscia hirsuta</i>	

### Appendix III

Air quality model residuals – Normal probability plot of residuals (a) and histogram of raw residuals (b).



## Appendix IV

Variables with lower correlations with the considered metrics. HBD, Diameter Breast hight (used as a surrogate of tree age); U100, Urban density within a 100m buffer; U200, Urban density within a 200m buffer; NVeg, ; NDVIc, NDVI measured at the green space center; PSR, Potential solar radiation ; Slop, slope ; Alt, . The symbol \* represents significance at  $p < 0,05$ ; \*\* represents significance at  $p < 0,01$ ; \*\*\* represents significance at  $p < 0,001$ .

	DBH	U100	U200	NVeg	NDVIc	PSR	Slop	Dist
<b>Richness</b>	-0,070	-0,265	<b>-0,324</b>	-0,154	<b>0,347</b> *	-0,245	0,237	0,237
<b>FR</b>	-0,060	<b>-0,320</b>	<b>-0,370</b>	-0,202	<b>0,334</b> *	-0,240	0,235	0,235
<b>LDVt</b>	<b>-0,436</b> **	<b>-0,516</b> ***	<b>-0,521</b> ***	<b>-0,429</b> **	0,304	-0,082	0,135	0,135
<b>LDVnit</b>	-0,272	<b>-0,337</b>	<b>-0,397</b>	<b>-0,328</b> *	-0,142	0,065	0,119	0,119
<b>LDVmes</b>	-0,277	<b>-0,477</b> **	<b>-0,459</b> **	-0,287	<b>0,422</b> *	-0,087	0,084	0,084
<b>LDVolig</b>	-0,220	<b>-0,348</b>	<b>-0,379</b>	-0,298	<b>0,335</b> *	0,033	0,186	0,186
<b>LDVHygr</b>	-0,173	<b>-0,310</b>	<b>-0,327</b>	-0,013	<b>0,349*</b>	-0,175	0,202	0,202
<b>LDVmesh</b>	0,007	-0,170	-0,127	-0,034	<b>0,365</b> *	-0,114	0,082	0,082
<b>LDVxer</b>	<b>-0,400</b> **	<b>-0,380</b>	<b>-0,432</b> **	<b>-0,393</b> **	0,056	0,078	0,076	0,076
<b>LDVcrust</b>	<b>-0,371</b> ***	<b>-0,518</b> ***	<b>-0,517</b> ***	<b>-0,413</b> **	0,084	-0,148	0,092	0,092
<b>LDVfoln</b>	-0,263	<b>-0,370</b>	<b>-0,382</b>	-0,250	0,007	0,048	0,026	0,026
<b>LDVfolbr</b>	-0,276	-0,217	-0,212	-0,019	<b>0,434</b> *	-0,218	0,238	0,238
<b>LDVfrut</b>	<b>-0,314</b> ***	-0,049	-0,105	-0,070	0,223	-0,046	<b>0,386</b>	<b>0,385</b>
<b>LDVsq</b>	0,058	-0,085	-0,059	-0,066	0,140	-0,079	0,119	0,119
<b>LDVlepr</b>	<b>-0,315</b> ***	-0,186	-0,139	-0,091	<b>0,316</b> *	-0,099	0,138	0,138

**Appendix V**

Plot of green spaces area (Area) and the percentage of lichen species richness increase (Richness).

